Demand Shocks Change the Excess Burden From Carbon Taxes

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8 February 2019

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February 5, 2019

Abstract

Two basic propositions underlying the economics of taxation – that excess burdens increase in elasticities and tax rates – are shown to cause the stringency of a Pigouvian tax to vary nonlinearly with output prices. This varying stringency of carbon taxation contributes to unfavorable competitiveness consequences following shocks to demand. Empirically, this paper measures the change in carbon tax stringency by structurally recovering the supply schedule for a particular industry such that elasticities and carbon tax rates change according to the distribution of output prices. Based on this supply function, the relationship between marginal excess burden, a measure of policy stringency from the industry's perspective, and product prices is estimated. Results for the Canadian cattle industry show that with moderately high output prices, supply elasticities are small, tax rates are low and the efficiency cost of a carbon tax (gross of environmental benefits), such as the one introduced in Canada, is less than \$0.01 per dollar tax revenue. As prices decline, supply curves become increasingly elastic, tax rates rise and marginal excess burdens grow rapidly.

Keywords: Carbon pricing; cattle; marginal excess burden; production function

JEL Codes: H23, Q1, Q5

*Early versions of this paper have been presented at the Canadian Economics Association Annual Meetings, Wilfred Laurier University and the World Congress for Environmental and Resource Economics. I appreciate the many helpful comments and suggestions from Bev Dahlby, Isaac Holloway, Mathias Kirchner, Nouri Najjar, David Rivers, Nicholas Rivers and James Rude. Partial funding for this research was provided by the Canadian Cattlemens' Association. Special thanks to the Alberta Ministry of Agriculture for sharing the data.

Weitzman's (1974) classic analysis is the starting point for environmental policy design in an uncertain world where it is challenging to update regulations. Building on this framework, substantial research suggests that carbon taxes are the preferred instrument for managing carbon dioxide (CO2e) emissions (e.g., Fell, MacKenzie and Pizer, 2012; Hoel and Karp, 2002; Newell and Pizer, 2003; Pizer, 2002; Weitzman, 2018). Yet, consensus on instrument choice has done little to quell industry uneasiness over lost competitiveness due to environmental policies. Industries point to the *quantitative* short-run implications of carbon taxation, with sectors subject to intense international competition expressing genuine concerns over leakage (Fowlie, 2009).[1] Weitzman-style arguments for carbon taxes are qualitative, offering little guidance on the quantitative effects for specific sectors. This is especially true for industries that face the prospect of sudden nonmarginal changes in market conditions. This paper measures competitiveness implications of nonmarginal demand shocks for trade-exposed industries. It demonstrates that demand shocks *nonlinearly* change industry-level excess burdens from carbon taxation in a way that has been underappreciated in environmental policy analysis.

The efficiency cost of a tax hinges on two fundamental propositions. First, excess burdens increase with the *square of the tax rate*. Second, excess burdens increase with the *size of elasticities*. Both statements hold even in the presence of externalities. A basic appreciation of these well-known precepts goes a long way towards reconciling the often conflicting perspectives on carbon taxation and industry competitiveness. Industry misgivings are usually based on deep concerns over lost competitiveness and leakage. These complaints are frequently dismissed as hyperbole or as founded on ideological or economic misconceptions. Yet, the fervor with which key sectors, even industries with a modest energy cost shares such as agriculture, fight carbon taxation signals that there may be more to this position than political beliefs. The contribution of this paper is to introduce and measure a previously overlooked distortion resulting from unilaterally implemented carbon taxation. This distortion is based on the startlingly simple observation – the elasticity of supply varies with output prices – but its consequences are subtle and underappreciated. A chief implication is that the marginal stringency of a carbon tax is not price invariant. Commodity prices can be volatile and, as prices fluctuate, the marginal excess burden *from a fixed carbon tax* changes nonlinearly in accordance with the *curvature* of the supply function. This is because both the *carbon tax*

[1] Agricultural producers, in particular, tend to fiercely oppose carbon taxation. Beef farmers, as an example, are among the most vocal opponents of Canada's carbon price. Several have claimed that if they "don't get [an] exemption [from the carbon tax] there's going to be a piling on, we'll be paying for the carbon on all of our inputs, we'll be paying the carbon on all of our production and we'll be stuck in the middle with no ability to actually pass any of those costs on" (Glowacki, 2017), that the government should "[l]eave cows out of carbon taxes" (Glowacki, 2017) and that a "tax could mean the difference between a breakeven year and suffering a loss" (Dyck, 2017).

rate and *elasticity of supply* increase as prices decline. Curvature is often economically unintuitive and not something that tax or environmental economists think about. But curvature provides a potential economic explanation for the several sector's position on carbon taxation. What's more, by offering this rationale, this paper gives broader insight into a range of industries' disparate views on environmental regulation and, more generally, into the taxation of commodities and resources.[2]

Curvature is often a footnote in tax and environmental policy models. This is likely for several reasons. The second moment of the supply function can be challenging to estimate, let alone think about. More importantly, the practical importance of curvature critically depends on the context studied. Even in this paper, it only matters because the carbon tax is invariant to demand shocks. In brief, a curvature distortion occurs because carbon levies are specific taxes whose stringency *from an industry's perspective* varies with the equivalent *ad valorem* rate, a rate that depends on output prices. The innovation of this paper is to outline a procedure to empirically measure how curvature influences policy stringency in a setting where it matters: levying a specific carbon tax on agricultural production. The sector studied is beef cattle production in Canada, but the methodology and implications are general. Beef production in Canada is an especially interesting case study. Internationally, livestock production is a large emitter of greenhouse gases[3] and, in January 2019, the Government of Canada introduces its "backstop" carbon price, a policy which serves as a price floor for subnationally designed and managed carbon pricing programs. Canada's federal backstop sets the minimum nation-wide price at \$20 per tonne carbon dioxide equivalent (tCO2e) emitted, increasing over a four year period, reaching \$50/tCO2e by January 2022. Thus, the empirical results are relevant for ongoing policy discussions.

The main intuition of this research is illustrated in Figure 1. This graph is the familiar depiction of domestic supply function in a small open economy with firms as price-takers. Figure 1 shows an upward sloping and *convex*, short-run supply curve alongside two horizontal demand curves which are, respectively, labeled: World Demand$_0$ and World Demand$_1$. World Demand$_0$ reflects a high (pre-tax) output price, p_0, while World Demand$_1$ is for a low (pre-tax) price, p_1. World Demand$_1$ can be thought of as the outcome following a negative demand shock. For ease of exposition, assume

[2]As an example, prominent energy firms such as Exxon and Suncor have publicly supported carbon taxation (WSJ, 2018), while less energy-exposed sectors including many small retail businesses strongly oppose these environmental regulations (CFIB, 2019).

[3]Global emissions from livestock equal 7.1 Gigatonnes (Gt) and represent 14.5% of all anthropogenic emissions (FAO, 2017). Of this, cattle (beef plus dairy) accounts for roughly 65% of emissions. In Canada, the agricultural sector contributed 1.7% to gross domestic product but 8.4% of national CO_2e emissions (ECCC, 2015) (these shares include forestry, fishing and hunting).

that the government unilaterally imposes a linear carbon tax on output equal to t. Two dashed horizontal lines represent the net-of-tax demand curves facing producers, one for each output price level. The tax reduces the price received by producers from p to p-t and producers respond to the tax by reducing output – indeed, in many industries (such as cattle), where output and emissions are complements, the purpose of carbon taxes is to reduce output (Phaneuf and Requate, 2016). Figure 1 makes clear the role of curvature. With high prices, p_0, the supply function is steep and a fixed tax of t elicits a small output response. As shown along the horizontal axis, when pre-tax prices equal p_0, the tax reduces output supplied by $t\frac{\partial Q_0}{\partial t}$. This response can be contrasted with an alternative scenario where low prices prevail and an identical carbon tax, t, triggers a substantially larger output response. The supply curve is notably flatter in the region around p_1 and, as shown along the horizontal axis, the reduction in output now equals $t\frac{\partial Q_1}{\partial t}$. The difference between the two scenarios results from the curvature or *change in slope* of the supply function that occurs as output prices vary.

Central to this paper's argument is how the two principles underlying the efficiency cost of taxation influence interest group perceptions. Both the role of elasticities and, to a lesser extent, of rates are demonstrated in Figure 1. Consider the situation of falling prices with a fixed and unilaterally implemented carbon tax. Excess burdens, the foregone producer surplus after fully recycling back tax revenues, are shown in Figure 1 by EB_0 and EB_1. Excess burden increases as prices fall. Two changes cause EB_1 to be larger than EB_0. First the supply response is larger at p_1 than p_0 and larger elasticities imply larger excess burdens. This is easy to see as $t\frac{\partial Q_1}{\partial t}$ is larger than $t\frac{\partial Q_0}{\partial t}$. The second effect is less obvious and depends on how excess burden is measured. Excess burden is typically a function of the *tax rate*, the specific tax as a percent of output prices. In Figure 1, the *ad valorem*-equivalent of the specific carbon tax increases as output prices decline. Said differently, lower prices imply a larger tax rate, even though the specific carbon tax remains unchanged. Both elasticities and rates contribute to the increase in the magnitude of foregone producer surplus. This relationship between prices and excess burdens likely explains why some groups, such as agricultural producers who are susceptible to commodity price volatility, view carbon taxes negatively. Interpreting excess burden in a particular way makes this clear: excess burden can be understood as measuring the willingness-to-pay to avoid a tax. This willingness-to-pay interpretation sheds light on industry responses to climate policy as it is directly linked to the policy's stringency. Stringency of a carbon price – the willingness-to-pay to avoid the tax – is not price invariant: *stringency increases as prices decline*. Moreover, the bite of climate policy changes *nonlinearly* as prices fluctuate. Prices are beyond trade-exposed firms' control, so it is this nonlinearity, the increasing stringency per dollar tax revenue, that helps to explain the opposition of key interest groups to carbon taxation.

Figure 1 also shows a second effect on tax revenues. Tax revenues, equal to tQ, are given by the rectangles labeled R_0 and R_1. Mechanically, for any fixed tax, more output leads to more tax revenue. But tax revenues also depend on an output response arising from changing prices. Graphically, Figure 1 shows that when prices equal p_0 and pre-tax output is Q_0, revenues equal rectangle R_0. Conversely, when prices are p_1, the tax revenue rectangle R_1 is disproportionately smaller. Evaluating the implications of price variation for carbon tax policy in small open markets requires accounting for both excess burden and tax revenue effects. The concept of marginal excess burden encapsulates both. Marginal excess burden (MEB) is defined as the change in excess burden divided by the change in tax revenues: $MEB = \frac{dEB}{dR}$ (e.g., Auerbach, 1985; Triest, 1990). Like its constituents excess burden and tax revenues, MEB varies with output prices. Moreover, curvature of the supply function implies a nonlinear curve for MEB as a function of product prices.

Curvature and the nonlinear relationship between MEB and prices matters for carbon tax policy because of leakage. Leakage is an unintended consequence of unilateral carbon taxation. When a single country levies a carbon tax, domestic production shrinks. Some share of this reduction is appropriated by *untaxed* foreign producers. That is, domestic policies elicit offsetting foreign responses. Leakage has three dimensions (Fowlie, Reguant and Ryan, 2016*a*,*b*). First is emissions leakage. Emissions leakage is the increase in foreign emissions that results from a decrease in domestic emissions. As less is produced domestically, more is produced offshore. Offshoring production involves offshoring some share of domestic emissions. Emissions leakage is fundamental to climate policy, but it is not the core point in this paper (although, several comments are included in the discussion).[4] The other elements of leakage include market transfers and rent leakage, each of which corresponds to a component in the MEB calculation. Market transfers, which are simply tax revenues in Figure 1, do not entail any efficiency loss – they are merely the surplus transferred from producers to the government. Rent leakage, represented by excess burden in Figure 1, is the efficiency cost of the tax. It is the competitiveness concern raised by industries such as agriculture.

The changing magnitude of supply responses (i.e., the changing size of elasticities) has been omitted in most empirical assessments of competitiveness and carbon pricing. As such, this study provides a unique opportunity to investigate a new dimension of the efficiency cost of taxation.

[4] Trivially, in Figure 1 excess burden equals domestic abatement.

Until recently, methods to recover reasonable analogues to supply functions were unavailable. Estimates of supply responses were typically point estimates, required strong assumptions or were estimated with bias due to unobserved firm-specific productivities. Yet, the relatively uncontroversial observation that the elasticity of supply decreases as global prices increase (and vice versa) has broad consequences for assessing the competitiveness repercussions of climate policy. Despite the conceptual simplicity, empirically determining whether the magnitudes are meaningful is less straightforward and so the remainder of this paper proceeds in several steps. First, the conceptual framework underlying the calculation of MEB is introduced in section 1. Also presented is the method used to trace the relationship between prices and MEB, a relationship that will be referred to as a stringency curve. While obviously connected to the large literature on optimal carbon tax models, this conceptual section largely eschews models of social welfare maximization, concentrating instead on an industry's perspective of carbon taxation. In this, carbon and commodity taxes appear largely the same to producers, regardless of the benefits associated with fewer emissions. The second step then represents the paper's main contribution. Section 2 outlines the empirical method used to construct an industry's supply schedule. The approach builds on De Loecker and Warzynski (2012) and Ganapati, Shapiro and Walker (2016), by using farm-level data on prices and quantities combined with assumptions on firm cost minimization to recover farm-specific marginal costs. The third step involves constructing counterfactual scenarios. Six distinct scenarios are developed representing different carbon tax bases and tax levels. Empirically, the focal industry is Canadian beef cattle producers. I show that these farmers should not be overly concerned with the competitiveness implications of Canada's carbon tax unless output prices are exceedingly low or the tax base (policy coverage) is broadened to include biological emissions from enteric fermentation (i.e., the digestive processes of cows). For example, at \$40/tCO2e, the excess burden (gross of environmental benefits) equals a paltry \$0.04 per dollar tax revenue at moderately low output prices and even less at higher prices. In contrast, broadening the tax base to cover methane emissions from cattle, the largest unpriced source of emissions in the country, can generate excess burdens of more than \$0.90 per dollar tax revenue at moderately low prices. Interestingly, even in this situation where emissions from enteric fermentation are taxed, the welfare cost per dollar tax revenue shrinks from \$0.90 to \$0.03 as output prices increase to a moderately high level.

Literature Review. The nonlinear stringency curves, the correspondence between MEB and commodity prices, rests on the carbon taxes' unilateral implementation and is an underappreciated feature of many studies on competitiveness and regulation. Two prominent streams of research on unilateral environmental regulation have developed.[5] The first looks at trade and the environment, placing special emphasis on the pollution haven hypothesis (Copeland and Taylor, 2004; Dechezleprêtre and Sato, 2017; Taylor, 2004). The second category applies an array of computable general equilibrium (CGE) exercises in an attempt to predict the costs of prospective regulation.

The pollution haven hypothesis posits that increasing the stringency of environmental regulation in one jurisdiction causes a shift of production to markets with weaker controls. (Differences in regulatory standards must, of course, be sufficiently large to introduce meaningful differentials in production costs (Cherniwchan, Copeland and Taylor, 2017).) Early work on trade and the environment found few effects of environmental regulation on trade flows, but recent evidence suggests that stricter standards do adversely influence net exports with unilateral environmental policy meaningfully affecting industry competitiveness (Brunnermeier and Levinson, 2004; Copeland and Taylor, 2004). Levinson and Taylor (2008), for instance, find that doubling abatement expenditures reduced net imports to the US by 40%. Similarly, Hanna (2010) finds that the US Clean Air Act Amendments led multinational firms to increase their foreign output by 9%, while Cherniwchan and Najjar (2018) show that environmental regulation changes firms' export decisions conditional on their productivity.

While providing vital insight into the relationship between unilateral environmental policy and competitiveness, the trade and environment literature struggles with three empirical challenges: measures of the stringency of environmental regulation are often imperfect (Brunel and Levinson, 2013), productivity heterogeneity determines which firms export and which do not (Cherniwchan and Najjar, 2018; Cherniwchan, Copeland and Taylor, 2017) and, most importantly, many proposed environmental regulations are out-of-sample or have minimal variation across jurisdictions. These challenges motivate the use CGE modeling to explore unilaterally implemented carbon taxes. Carbone and Rivers (2017) review a wide-range of CGE studies, finding that in most cases unilateral carbon prices have modest effects on domestic economies. Reductions in welfare are rarely greater than 2% for plausible policy scenarios. Yet, key modeling choices often drive CGE estimates. For instance, most CGE models assume constant returns to scale and imperfect substitutability between domestic and international production (i.e., the Armington framework).[6] Deviations from

[5] Markusen (1975) and Hoel (1996) are prominent, early theoretical contributions studying the effect of carbon pricing on international competitiveness. These papers showed that the optimal method of alleviating the competitive effects of unilateral environmental policy is to adjust prices at national borders via instruments such as tariffs on imports and subsidies on exports. The legality of these instruments is uncertain and, to date, no country has pursued a border adjustment strategy (Fischer and Fox, 2012; Ismer and Neuhoff, 2007).

[6] Imperfect substitutability reflects factors such as difficult to observe trade barriers, preferences for domestic over

these assumptions suggest that the welfare losses from unilateral regulation could be much larger. Babiker (2005), for instance, allows for increasing returns to scale and easier reallocation of production across jurisdictions, ultimately finding that the welfare costs of unilateral climate policy can exceed 6% of GDP.[7]

Beyond its emphasis on industry competitiveness, this study also fits within the growing literature on heterogeneity and externalities. Recent research, including Griffith, O'Connell and Smith (2017); Jacobsen et al. (2018); Knittel and Sandler (2013), builds on the seminal results in Diamond (1973) to examine welfare consequences of corrective taxation when consumers are heterogeneous and policies are second-best. Likewise, Andersen (2018), Li and Sun (2015), Anouliès (2017) and Tombe and Winter (2015) investigate the interaction between firm heterogeneity and environmental regulation. Andersen (2018) shows that uniform regulation on heterogeneous firms generates confounding effects. The least efficient firms exit the market, increasing the average productivity of the remaining firms (hence lowering prices), yet this is offset by the reduction in the variety of products available. Li and Sun (2015) and Anouliès (2017) investigate the welfare effects of permit allocation rules, emissions taxes and standards when firms are heterogeneous. Tombe and Winter (2015) study how intensity standards lead to the misallocation of the resources and lower aggregate productivity. The broad implication of firm heterogeneity, one to which this paper contributes, is that uniform policies applied to industries with heterogeneous firms creates winners and losers, influences output, changes entry and exit decisions and may elicit unexpected responses. Still, the approach taken here offers a shift of perspective, one that presents new insights. It focuses on the structural characteristics of a specific market and is motivated by what seems like an excessive aversion to climate policy. This research also starts from the economics of taxation, rather than externality correction. This is a twist on existing approaches to carbon taxation, even though

foreign goods or poorly developed distribution networks.

[7]The trade and environment and CGE literatures tend to look at aggregate economic effects. Complementing these economy-wide results is a voluminous set of studies on the implications of climate change on agricultural yields and land values (e.g., Brohé and Greenstone, 2007; Mendelsohn, Nordhaus and Shaw, 1994; Schlenker and Roberts, 2009; Severen, Costello and Deschenes, 2016). Academic studies investigating the empirical consequences of carbon pricing on specific agricultural commodities such as cattle are surprisingly scarce. Indeed, the papers that do exist apply mathematical programming models that share properties with CGE models. Peters et al. (2001), for instance, find that a \$100tCO$_2$e tax would reduce beef production by 0.6% and decrease overall agricultural producer surplus by a modest 0.2%. Schneider and McCarl (2005) find similar results with a \$100/tCO$_2$e tax leading to a 0.9-3.7% reduction in net farm income. Finally, a handful of papers econometrically investigate unilateral carbon policy on variables such as jobs, gasoline consumption and natural gas usage (examples from Canada include Antweiler and Gulati, 2016; Lawley and Thivierge, forthcoming; Rivers and Schaufele, 2015*b*; Scott, 2015; Yamazaki, 2017). Still, only Rivers and Schaufele (2015*a*) has econometrically studied the implications of carbon taxes on agriculture. Using a difference-in-differences design, Rivers and Schaufele (2015*a*) examine the effect of British Columbia's carbon tax on the international trade of a series of agricultural commodities, including cattle. That paper finds no evidence of an effect of carbon pricing on net trade (which is not the same as no effect).

MEB (and the related concept marginal cost of public funds) is a direct input into environmental cost-benefit analysis (Dahlby, 2008; Sandmo, 1975; Triest, 1990).

1 Conceptual Framework

Carbon taxes are designed to correct environmental externalites and align private and social costs and benefits. Unilaterally implemented carbon taxes also change the competitiveness of domestic industries. The benefits from reducing CO2e emissions are appropriately measured using the social cost of carbon, an estimate of the marginal damage per tonne emitted. In contrast, the term competitiveness is vague and frequently used as a catch-all without precise definition (Carbone and Rivers, 2017). Vague notions of competitiveness are unhelpful, so this paper treats competitiveness as the efficiency cost of a unilaterally implemented carbon tax and measures it via MEB. MEB is the ratio of a change in excess burden to a change in tax revenues.[8] In the context of a specific carbon tax, MEB varies with output prices as both the tax rate and supply elasticity vary with output prices. This section starts by presenting how MEB is calculated via its relationship to analogous statistic, the marginal cost of public funds. It then explains how the stringency curves (i.e., the correspondence between MEB and prices) are calculated by nonparametrically approximating the curvature of the supply function using arc elasticities calculated at different price levels. Stringency

[8] While not the focus of this study, measurement of excess burden can be formulated as a sufficient statistic problem using the approach outlined in Chetty (2009) and Jacobsen et al. (2018). A sufficient statistic approach frames the change in welfare from a tax as the wedge in a planner's problem. Let cattle producers' post-tax profit functions be given by $\pi = (p - t)Q - c(Q) - F$, where $(p - t)$ is the post-tax price, Q is industry output, $c(\cdot)$ is a well-behaved cost function and F is fixed costs. The first-order condition is $p - t - c' = 0$. The sufficient statistic version of the planner's problem is:

$$W = \pi + tQ = (p - t)Q - c(Q) - F + \Phi + tQ$$

where F is fixed costs and Φ is a stock externality that does not depend on cattle producers' decisions (i.e., Canadian cattle producers are too small to influence the stock global CO2e). Differentiating with respect to t:

$$\begin{aligned} \frac{dW}{dt} &= -Q + (p - t - c')\frac{\partial Q}{\partial t} + Q + t\frac{\partial Q}{\partial t} \\ &= t\frac{\partial Q}{\partial t} \end{aligned}$$

where the producer's first-order condition was used in the second line. Excess burden then can be defined as

$$\begin{aligned} EB \equiv dW &= t\frac{\partial Q}{\partial t}dt \\ &\approx t^2\frac{\partial Q}{\partial t}. \end{aligned}$$

for a small initial tax. A similarly simple framework can be formulated to determine the carbon tax that maximizes social welfare given benefits from reduced emissions.

curves illustrate how the competitiveness effects of a specific carbon tax varies with demand shocks.

Marginal Excess Burden

MEB is used to measure the stringency of a carbon tax from an industry's perspective. Several methods are available to calculate MEB. The method adopted here is to approach MEB via the intimately related to the concept of marginal cost of funds (MCF). This path is selected for two reasons. First, when carbon taxes are embedded in a broader suite of taxes, such as in the frameworks developed by Sandmo (1975) and the double-dividend literature (e.g., Goulder, 1995), expressions for optimal taxes depend on the MCF. Thus it is useful to link these concepts. (Optimal taxes are not the focus of this paper, but the results are clearly related to the optimal carbon tax literature.) The second reason for starting with the MCF is pragmatic and expository. The MCF for an industry facing a perfectly elastic demand curve is formulated so that it unambiguously illustrates the two principles underlying the efficiency cost of taxation as highlighted in the introduction.

MCF is defined as a dollar-valued measure of the welfare loss from raising tax revenues evaluated at the tax distorted prices (Dahlby, 2008). Its relationship to MEB is given by the simple formula (Triest, 1990):[9]

$$MEB = MCF - 1.$$

In competitive markets, where in the limit firms face perfectly elastic demand and abating emissions involves output contraction, the marginal cost of funds equals:

$$MCF = \frac{1}{1 - \frac{t}{p-t}\eta(p)} \tag{1}$$

where t is the per unit output carbon tax (i.e., the effective carbon tax in \$ per unit output), p is the output price and $\eta(p)$ is the elasticity of supply, which is a function of p. Both properties of the economics of taxation are clear in (1): the efficiency cost of a tax increases in the tax rate and size of elasticities. The tax rate is given by $\frac{t}{p-t}$, the ratio of the tax to the post-tax price. As prices increase, this rate falls and vice versa. All else constant, as the rate decreases, the denominator of (1) gets closer to one and the MCF falls. Identical reasoning applies to the size of the elasticity

[9] In general, it is necessary to normalize MEB by a price index reflecting a money-valued change in the utility of income evaluated at pre- to post-tax prices. In this context however, this index equals one, so is omitted.

of supply, η. As output prices fall, the elasticity of supply increases and the denominator of (1) shrinks. This increases the MCF and the excess burden of the tax. (1) shows the central point of the paper. As firms experience price fluctuations (i.e., demand shocks), the stringency of a fixed carbon tax, measured by MEB, varies in accordance with the tax rate and the size of the elasticity of supply.

Using (1), it possible to rewrite MEB as:

$$\begin{aligned} MEB &= \frac{1}{1 - \frac{t}{p-t}\eta(p)} - 1 \\ &= \frac{\tilde{\tau}\eta(p)}{1 - \tilde{\tau}\eta(p)} \end{aligned} \tag{2}$$

where the second line in (2) reduces (1) to its essential two components: tax rates and elasticities. The tax as a percent of the post-tax producer price is given by $\tilde{\tau} = \frac{t}{p-t}$. Larger tax rates arise through two means. First is the price channel that has been discussed. Second is when the tax levels increase for a given price. For example, when Canada increases the stringency of its backstop policy on January 1, 2020, the tax will increase from \$20 to \$30/tCO_2e and the *ad valorem*-equivalent carbon tax rate will increase.

The second parameter in (2) is the responsiveness of quantity supplied to changes in output price. The main contribution of this study involves constructing a marginal cost schedule for a sample of cow-calf firms and then determining how the slope of the supply function varies with price. Because the supply curve is constructed as an order list of Lagrange multipliers, it cannot be represented analytically as the second derivative of a pre-defined functional form. Instead, the relationship between MEB and price must be traced out by pairing values in MEB-price space. More precisely, both MEB and the elasticity of supply are nonparametrically estimated along arcs of the supply curve; thus arc, rather than point, elasticities are used. (Arc elasticities have a long history in economics (Allen and Lerner, 1934) and represent the elasticity between two points along the curve.) These midpoint arc elasticities are calculated as:

$$\eta(p_i) = \frac{\frac{q_j - q_k}{1/2(q_j + q_k)}}{\frac{p_j - p_k}{1/2(p_j + p_k)}} \qquad \text{for} \quad k < j \tag{3}$$

where q_j and q_k reflect two points on the constructed supply curve (i.e., firms' marginal costs) with p_j and p_k as the exogenous prices. For each i, which represents the midpoint along arc length

$p_j - p_k$, these arc elasticities are first calculated. The arc elasticities are then used to determine MEB according to (2), which is then plotted against price in price-MEB space. The figures in the results section use arc lengths of $12.50 price increments to calculate these arc elasticities. Practically, this approach entails linear approximating the unknown curvature of the supply function via a method akin to polynomial interpolation.

2 Empirical Methodology

The empirical methodology is presented in five parts. First, the data are reviewed. An abbreviated overview of the cattle sector is included, as this sector is unfamiliar to many. Second, the method for obtaining firm-level marginal costs from production data and assumptions about cost minimization are discussed. The econometric approach used to estimate critical production function parameters is then presented. The production function yields an output elasticity. Given the importance of unobserved firm-specific productivities, estimating the production function is tricky. Selection bias and simultaneity have the potential to generate significant bias in the elasticity. Once the output elasticity is estimated, it is possible to recover marginal costs and then construct an ordered list of these costs representing the sample's supply function. The subsequent results section then adjusts this supply function according to the carbon tax counterfactual scenarios which are reviewed fourth in subsection 2.5. The counterfactual scenarios reflect the tax-induced cost-of-production increase due to the Canadian backstop carbon tax policy as well as for two more stringent carbon pricing scenarios where the tax based is expanded to cover an otherwise omitted source of emissions: enteric fermentation. Appendix A contains a general overview of the policy setting, carbon pricing in Canada, for additional background.

2.1 Farm-Level Data

Background on Cattle Industry

The cattle industry is big – in 2015, it generated more than $78B in revenues in the US (USDA, 2016) while primary production of cattle and calves contributing roughly $10B to the Canadian economy (Statistics Canada, 2016) – but its basic structure is unknown to many. Taking some liberties with its description, the Canadian beef cattle industry can characterized by four stages. Cow-calf operations comprise the first stage of the production process and this is the focus of this study. Cow-calf farms calve, wean and background new animals.[10] Feeder calves, an intermediate output in the beef supply chain, are sold by the cow-calf operations to feedlots, once the animals have achieved a mass of roughly 750 pounds. Feedlots rapidly increase the mass of the animals through intensive feeding before selling fed cattle, another intermediate output, to packers at a mass of approximately 1450 pounds. Packers slaughter the fed animals and prepare cuts of meat for retailers and consumers. Calves are measured in pounds and prices are quoted in dollars per one hundred pound "live weight" increments, called hundredweight. Hundredweight is abbreviated as cwt. All prices in this study are quoted in dollars per hundredweight ($/cwt). The terms calf, cow, head and animal are used interchangeably throughout.

The policy relevance of this paper's empirical results depends on on two assumptions about the Canadian cattle market. First, product prices must vary over a meaningful range. Second, producers must face perfectly elastic demand. Appendix B discusses and provides evidence for both assumptions. Prices do span a wide range and treating cattle farmers as price-takers appears to be a mild assumption.

Data

The data used in this analysis are from the Province of Alberta's Ministry of Agriculture and Forestry. Between 1995 through 2005, longitudinal data were collected on a representative sample of cow-calf enterprises with herd sizes ranging from eight animals to more than 800 head.[11] Ministry officials selected the sample to match the profile of the province's cattle sector, but little information is available on the specific sampling methodology. In total, 250 operations participated in the survey but their coverage is incomplete. Only 210 farms are surveyed in multiple periods after observations with missing data on any of the input variables are omitted. Further, the panel is unbalanced with 45 farms appearing for the entire time span.

Despite the limited number of operations, the information provided is rich. Data on farm-level

[10]Technically, cow-calf and backgrounding operations are distinct, but, in Canada, virtually all cow-calf farms also include a backgrounding operation.

[11]The long-run minimum efficient scale for an Albertan farm is unknown. However, Canfax Research Services hypothesizes that it is between 200 and 800 head, a size consistent internationally (Canfax, 2012). It is reasonable to assume that the long-run average cost curve is quite flat.

prices and physical quantities are available. Outputs include pounds of calves, the main variable of interest, and also pounds of cull cows and bulls (recall there are 100 pounds in a hundredweight). Two calf prices are observed for each farm. First, there is information on the realized sales weighted average annual price of output per hundredweight. These are the actual prices received by the producer. Futures prices are also available (as is basis for Alberta). Arguments support using either futures or realized prices in this analysis. Futures reflect the information set at the point where input allocation decisions were made. Realized prices reflect the actual decisions made. Ultimately, both series generate similar results, so the analysis below uses realized prices. The average realized price in the sample is $114.05/cwt with a standard deviation of $22. The range of output prices is wide, spanning from $63 to more than $250/cwt.[12] The Canadian bovine spongiform encephalopathy (mad cow) crisis occurred during this period. This event was an unanticipated negative shock to the industry. From May 2003 through to the end of 2004 (depending on the trading partner as several opened their borders prior to this point), the Canadian border was effectively closed to exports and domestic prices were dramatically lower than in other periods.

Four inputs are used in this analysis: materials, labor, land and capital and feed. Information is provided for labor in terms of the number of hours allocated to cattle per enterprise. On average, 1250 hours per year were devoted to the cattle operation. 87.9% of these hours were recorded as "uncompensated", which means that this is time allocated by owner-operators. There are two issues with these labor data. First, it is likely that this variable is measured with error. It is easy to imagine an operator over- or under-apportioning their recorded time, particularly if they have off-farm employment or a supplementary crop enterprise. Further, it is not immediately obvious what these individuals' opportunity costs are. The Ministry applies a rule-of-thumb based on a "reasonable" market wage. This rule is applied uniformly, so disregards heterogeneity. Land is measured in acres devoted to cattle. The average farm size is 3364 acres. Land is a slow changing input which is combined with capital, another "sticky" input. Capital includes machinery and buildings and other slowly evolving stocks. Heated waterbowls and tractors are key items included in capital. Feed is the largest cost for cow-calf enterprises. The data on feed quantities are reliable as this is carefully tracked; the farm-specific price is likely measured with error, however. Similar to uncompensated labor, a notable share of feed is internally supplied (i.e., grown on-farm), hence its true market price is less obvious. For internally supplied feed, even though they were instructed to record market prices for feed, farmers may have instead recorded feed at cost. The final input is materials. Similar to Ganapati, Shapiro and Walker (2016), energy is grouped with materials

[12]For comparison, in 2017, Alberta calf prices have ranged from $133.44 to $166.63.

to create a single variable. Materials is comprised of farm fuel, electricity, business expenses (e.g., telephone), custom work and veterinary charges. Both quantities and prices of these data are less prone to measurement error as the vast majority of these inputs are purchased via market transactions. The mean revenue share of materials, a variable used in the next subsection, is 12.5%.

2.2 Recovering Marginal Costs

In industries such as beef cattle production, marginal costs determine production. Hence, recovering the schedule of marginal costs provides a method to determine industry output for any given price. The approach to recovering marginal costs follows De Loecker and Warzynski (2012) and Ganapati, Shapiro and Walker (2016). Let farm i in year t produce Q_{it} pounds of live cattle (calves). Output, Q, is a function of both variable and sticky inputs. To keep things descriptively straightforward, consider only two inputs. Variables inputs, denoted V_{it}, are comprised of materials and energy. Capital is dynamic and denoted with K_{it}. Timing assumptions identify variable from sticky inputs. Each operation has a farm-specific productivity Ω_{it}, so that the production function is $Q_{it} = Q_{it}(V_{it}, K_{it}, \Omega_{it})$. This farm-specific productivity may include factors such as managerial ability, local weather patterns or, a characteristic that is particularly important in agriculture, land quality. Syverson (2011) discusses how the distribution of productivity can be large even in homogeneous product industries. Producers minimize variable costs after conditioning on dynamic inputs and solve the Lagrangian:

$$\mathcal{L}(V_{it}, K_{it}, \lambda_{it}) = P_{it}^{V} V_{it} + R_{it} K_{it} + \lambda_{it}[Q_{it} - Q_{it}(V_{it}, K_{it}, \Omega_{it})]$$

where P_{it}^{V} is the price of materials and energy (variable inputs), R_{it} is the price of capital inputs and λ_{it} is the Lagrange multiplier.

The producer's first-order condition is:

$$\frac{\partial \mathcal{L}}{\partial V_{it}} = P_{it}^{V} - \lambda_{it} \frac{\partial Q_{it}(\cdot)}{\partial V_{it}} \tag{4}$$

and, at the optimum, $\frac{\partial \mathcal{L}}{\partial V_{it}} = 0$. It is possible to rearrange (4) and multiply by $V_{it}Q_{it}/V_{it}Q_{it}$ and

P_{it}/P_{it} to obtain:

$$\frac{P_{it}}{\lambda_{it}} = \theta \left[\frac{P_{it}^V V_{it}}{PQ_{it}} \right]^{-1} \tag{5}$$

This expression has three elements. The left-hand side of (5) is the multiplicative markup, prices divided by marginal costs, for farm i in year t. λ captures the effect of relaxing the production constraint in the cost minimization problem. It is the shadow price on output and therefore represents marginal costs. These marginal costs are the variables of interest in this study. The right-hand side of (5) is comprised of two terms. First, $\frac{P_{it}Q_{it}}{P_{it}^V V_{it}}$ is the inverse share of materials and energy costs relative to revenues. Next, θ is the output elasticity, a primitive parameter. This is the elasticity of cattle output with respect to materials and energy. Prices, P, and the revenue share of variable inputs, $\frac{P_{it}Q_{it}}{P_{it}^V V_{it}}$, are observable in data. θ must be estimated and its estimation is discussed next. Given each of these components, it is possible to calculate farm-level marginal costs, $\lambda_{it} = MC_{it}$, for each operation and year. Ordering these observation-specific variables then provides an analogue to the supply function for the sample, a supply function that is used to calculated MEB in the counterfactual scenarios.

Economists studying commodity markets typically assume that producers are price-takers and the competitive equilibrium obtains. Markups are consistent with this assumption in the short-run under several conditions (Carlton and Perloff, 2015).[13] First, producers require a return to fixed factors such as land. Available land for production is usually fixed in the short-run; new purchases or new leases are required to expand operations. Price will equal marginal costs for the marginal producer, but so as long as there is a fixed factor and some cross-firm heterogeneity in, say, managerial ability or land quality, the marginal cost for any specific operation will not necessarily equal price. Rather producers will earn a contribution towards their fixed costs and this contribution is the difference between price and variable costs (i.e., quasi-rents). Second, and more relevant for the cattle market, farmers usually provide uncompensated labor to the business. As discussed, the dataset actually records uncompensated labor and, while an imperfectly measured variable, it is clear that it is an important input in the production process.

Recovering marginal costs from (5) depends on several assumptions. First, producers must be cost minimizers. Given the timing of input allocation decisions, cost minimization is viewed as

[13] Of note the average mark-up for cow-calf operations is 4.4%, significantly less than the 10-40% found in Ganapati, Shapiro and Walker (2016). Small mark-ups are expected in industries that more closely resemble perfect competition.

innocuous in this context. Next, this methodology implicitly assumes that all producers have the same technology both across firms and across time (De Loecker and Warzynski, 2012; Ganapati, Shapiro and Walker, 2016). This assumption is stronger. Two features of the analysis lend it support, however. First, the period of analysis is relatively short 1995 to 2005, and there were few obviously identifiable changes to cow-calf production processes over this period. Second, the data permit several tests for farm-level heterogeneity according to the firm's location in space and land quality. Operations in the Northern part of Alberta, for instance, use more feed and less open grazing due to longer winter seasons. Re-estimating the output elasticity including interactions between soil types and grass types, demonstrates few statistically significant differences in the output elasticity heterogeneity, along with minimal substantive differences in the point estimates. Based on these results, the assumption of common technology appears reasonable. Finally, implicit in this approach to recovering marginal costs is that heterogeneity in productivity determines marginal costs heterogeneity.

2.3 Estimating the Production Function and Output Elasticity

Recovering firm-specific marginal costs requires estimating the output elasticity, θ. Obtaining unbiased estimates of production function parameters is notoriously challenging. Both simultaneity bias, where firms choose inputs according to their specific productivities, and selection bias, as low productivity firms are more likely to exit, have the potential to influence estimates. The preferred output elasticity in this paper is estimated via Ackerberg, Caves and Frazer's (2015) control function method. The main idea of this approach is that the choice of inputs can be used to formulate a control function that enables the farm-specific unobserved productivity term to be estimated. That is, observed capital decisions are combined with assumptions on timing and monotonicity to proxy for unobserved productivity. To support the plausibility of the elasticity from this method, least squares and fixed approaches are also used as robustness checks.

The basics of the method are as follows. Start with a production function:

$$Y_{it} = f(\mathbf{X}_{it}) \exp(\phi_{it})$$

where Y_{it} is output in hundredweight of live calves, $\mathbf{X}_{it}$ is a vector of inputs and ϕ_{it} is an error term. While the model estimated below is translog with four inputs, for expositional simplicity, this description uses a Cobb-Douglas in logs with only materials and capital:

$$y_{it} = \beta_m m_{it} + \beta_k k_{it} + \omega_{it} + \xi_{it}$$

where lowercase variables represent logged values. ω_{it} is a farm-specific productivity term, while ξ_{it} is a random innovation representing unanticipated shocks and measurement error. The distinction between the unobserved productivity component and the random innovation is important. Farm-specific productivity, ω_{it}, includes factors that are known to the farmer before she chooses her inputs. It includes features that influence input choices such as managerial ability, expected heat stress and land carrying capacity. The random component is unknown to both the farmer and the analyst at the time when inputs are selected. The coefficient of interest is β_m, the elasticity of output with respect to materials and energy. Obtaining an unbiased and consistent estimate of β_m depends on the properties of the ξ_{it} and ω_{it} terms. These terms are treated three ways:

$$\omega_{it} + \xi_{it} = \zeta_{it} \tag{6}$$

$$\omega_{it} + \xi_{it} = \gamma_i + \psi_t + u_{it} \tag{7}$$

$$\omega_{it} + \xi_{it} = \omega_{it} + \nu_{it} \tag{8}$$

Each of (6), (7) and (8) corresponds to a different estimation method and distinct assumptions about unobserved productivity. (6) pools the random innovation and productivity elements into a single error term, referred to as ζ_{it}. The production function is then estimated using pooled least squares. (6) is tantamount to omitting the farm-specific productivity and hence the danger of this approach is that the output elasticity may be subject to various sources of bias.

(7) attempts to address this prospective bias by assuming that $\omega_{it} = \gamma_i + \psi_t$. Productivity shocks are either time invariant at the farm-level or are common to all producers in this specification. The model is then estimated by adopting a fixed effects specification. Residual bias in fixed effects models arises from time-varying, farm-specific productivity shocks that are known to the producer but unobserved by the econometrican. While fixed effects specifications have substantial merit, they tend to generate elasticities that are implausibly small. Further, fixed effects can exacerbate measurement error problems.

As stated, while both standard least squares and fixed effects models are estimated for robustness, the preferred model obtains the output elasticity using the control function or proxy method as in (8) (Ackerberg, Caves and Frazer, 2015; Levinsohn and Petrin, 2003; Olley and Pakes, 1996). The Ackerberg, Caves and Frazer (2015) approach can be thought of as a two step process. The intuition to avoid simultaneity and selection bias is this. If the unobserved farm-specific productivity is assumed to follow a $AR(1)$ Markov process, then a first stage can be formulated to remove measurement error and unanticipated shocks from the output variable. That is, the firm's choice of inputs can be used to formulate a control function in which the endogeneity problem is solved. After completing this stage, it possible to invert the factor demands to solve for productivity as a function of observables. A second stage is then formulated by generating a series of moment conditions for this variable that follows from the first stage. It is then possible to estimate an unbiased output elasticity in this second stage.

The control function approach proceeds as follows. A general production function (in logs) is:

$$q_{it} = f(\mathbf{x}_{it}; \beta) + \omega_{it}$$

where ω_{it} is the unobservable, farm-specific productivity term. An assumption is required about the evolution of the productivity process. It is typical to treat it as a first-order Markov process (e.g., Ackerberg, Caves and Frazer, 2015; Olley and Pakes, 1996, and many others):

$$\omega_{it} = g(\omega_{it-1}) + v_{it}$$

which feeds into period t's capital decision[14,15] and enables the production function to be specified as:

$$y_{it} = \beta_m m_{it} + f_t(k_{it}, i_{it}) + \xi_{it}$$

where $f_t(\cdot)$ is a function that implicitly depends on the unobserved productivity through a farm's observable choice of capital inputs. Estimating this function provides predicted values of $\hat{\beta}_m$ and $\hat{f}_{it}$. Given these values it is possible to generate moment conditions:

$$\mathbf{E}(\hat{v}_{it}(\beta) z^q_{it}) = 0 \tag{9}$$

[14]That is, the capital transition equation is $k_{it} = (1-\delta)k_{it-1} + i_{it-1}$, where δ is depreciation and i is investment. Investment in period t is a *monotonically* increasing function of ω_{it} and observables: $i_{it} = I_t(k_{it}, \omega_{it})$, and I_t can be inverted to yield firm-specific productivity: $\omega_{it} = I_t^{-1}(k_{it}, i_{it})$.

[15]Breeding stock is considered capital.

where z_{it}^q are the instruments. The instruments include the contemporaneous logged inputs and their interactions. Finally, generalized method of moments is applied to select the β coefficients which minimizes (9) and the output elasticity is obtained. Standard errors for this output elasticity are derived by repeating this procedure for a series of bootstrapped samples.

2.4 Estimates of the Output Elasticity

Four inputs, materials, land and capital, feed and labour, along with a translog specification, are used to estimate the output elasticity via least squares, fixed effects and control function methods. Table 1 shows the relevant output elasticity for materials for pooled least squares, fixed effects and control function estimation methods. Pooled least squares yields an elasticity of 0.17. As is typical, this value is larger than the parameter found via a fixed effects specification. The fixed effect model attenuates the output elasticity. It equals 0.09. The right-most column contains the preferred control function approach. Using the control function methodology, the output elasticity for materials equals 0.16.[16] This estimate is used throughout the results section. For context, Mundlak, Butzer and Larson (2012) apply a fixed effects approach to cross-country panel data and estimate a materials output elasticity equal to 0.10 for agriculture, a value similar to the one in Table 1.

The final row in Table 1 shows the implied long-run returns to scale. At 0.95 and 0.92, respectively, the least squares and control function methods suggest similar returns to scale for beef cattle farming. Cow-calf farms operate at near constant returns to scale. Interestingly, this finding is aligned with the anecdotal, conventional wisdom on cattle farming. The returns to scale estimate from the fixed effect specification strongly contrasts with these estimates. It suggests strongly diminishing returns to scale equaling 0.54. Both the returns to scale and the output elasticity estimates reduce the credibility of the fixed effects model, signaling that these estimates are more likely to produce biased conclusions about the competitiveness implications of carbon taxes on cattle farmers.

[16] Clustered standard errors are estimated for the least squares and fixed effects specifications. Clustering is on individual farms. For the control function model, standard errors are bootstrapped by reestimating the output elasticity for different samples.

2.5 Counterfactual Carbon Pricing Scenarios

The final step of the empirical methodology involves constructing the counterfactual scenarios. Six carbon pricing scenarios are considered. These are outlined in Table 2. Table 2 presents the effective tax – that is, the per unit output cost increase – for two levels of tax measured in dollars per tCO2e and three coverage levels. MEB, as shown in equation (2), depends on the *effective* carbon tax rate measured in dollars per hundredweight. The effective tax is the product of two factors: the tax rate per tonne of tCO2e and the direct and indirect emissions covered by the policy measured in tCO2e/cwt. The taxes considered are \$20 and \$40/tCO2e. Often these tax levels are interpreted directly as the stringency of the policy. Equally important is the coverage, or tax base, of the policy, which is captured in the latter component.

Canada's existing carbon pricing policies focus on emissions from the combustion of fossil fuels. This covers approximately 70% of national emissions, yet the backstop policy exempts two major sources of agricultural emissions that are relevant to the empirical analysis. First, relief is granted to "gasoline and diesel fuel used by registered farmers in certain farming activities". This applies to dyed fuels used in on-farm production. Agricultural operations in Alberta, British Columbia and provinces adopting the backstop policy are granted this exemption, so the carbon levy will have little direct impact gasoline and diesel costs. As mentioned, provinces are free to tailor their carbon pricing systems. Quebec, for instances, is not exempting dyed fuels. As a consequence, the first two carbon pricing scenarios in Table 2 reflect, first, the backstop policy and, second, this backstop policy plus a tax on fuel used on-farm.

All Canadian carbon pricing policies also exempt emissions from enteric fermentation. Enteric fermentation, or methane released from digestive processes, is the largest unpriced source of greenhouse gases in many countries, including Canada. (Globally, no country levies fees on enteric fermentation.) In Canada, agriculture contributes 1.7% to GDP but 8.4% of its total emissions (ECCC, 2015). In Alberta, the jurisdiction from which the data are from, beef cattle emitted 6.8MtCO2e or 3% of the province's total emissions (AAF, 2003). While taxing enteric emissions is less administratively straightforward than taxing diesel (Neufeldt and Schäfer, 2008; Slade, 2018), excluding enteric fermentation from the tax base is tantamount to a tax break for the beef industry. As a result, the third scenario adds both farm fuel and enteric fermentation to the Canadian backstop policy.

Table 2 shows the effective carbon taxes measured in units of output under the different scenarios. For a \$20/tCO2e tax, like the one Canada mandates in 2019, costs-of-production will increase by \$1.55/cwt under the backstop policy. That is, this \$1.55/cwt is the value obtained for the \$20/tCO2e tax, after converting it from \$/tCO2e to \$/cwt, according to the tax base prescribed by Canada's carbon pricing backstop policy. Applying the same procedure, but repealing the farm fuel exemption, increases the effective tax to \$1.91/cwt. Finally, if enteric fermentation were included in the tax base, costs increase nearly 7-fold to \$12.80/cwt. Table 2 also shows the corresponding estimates at \$40/tCO2e which correspond to \$1.87/cwt, \$2.58/cwt and \$24.35/cwt for the three scenarios.[17]

Appendix C outlines how these effective taxes are calculated. Estimates of the effective taxes are determined by merging several sources. The precision of these values represents the biggest source of uncertainty in the empirical exercise and standard caveats therefore apply. Despite this caution, the estimates do reflect the best available information for the Albertan context studied. The methodology involves combining enterprise budgets (e.g., from AAF, 2015) with estimates from the economics literature and a computable general equilibrium model (Rivers, 2017) to establish the expected cost increase on beef production inputs for a given tax and coverage level. An example helps to highlight how these values were determined. Electricity is used as a direct input in cattle production and as an input in feed costs. Enterprise budgets (i.e., cash flow models) are available for both cow-calf and feed operations in the province of Alberta. These budgets are based on a typical operation and combine physical units and prices. Electricity enters into the enterprise budgets as a line item expense. This line item expense was inflated by the expected carbon tax-induced increase in electricity costs. This was done for both direct electricity costs for the cattle operation and for the indirect electricity costs that arise through the feed line item (feed typically comprises nearly 50% of the total cow-calf costs). The increase in electricity costs were calibrated based on research by Brown, Eckert and Eckert (2017). Brown, Eckert and Eckert (2017) develop a structural model of Alberta's electricity sector allowing for installed generation technology and the prospect of strategic behavior by market participants.[18] Implicit in this method

[17]The disproportionately smaller increase in costs as rates double from \$20 to \$40/tCO2e are driven primarily by assumptions about Alberta's electricity sector. The province's power sector, a large energy cost in agriculture, combines a rapidly changing electricity generation fuel mix with market power and the output-based allocation system such that a \$40/tCO2e carbon tax, as comes into effect in 2021, is forecast to produce a disproportionately smaller increase in the price of electricity (Brown, Eckert and Eckert, 2017). Hence, there is not a doubling of costs as rates increase. An alternative interpretation of this is that as carbon costs increase, producers are more likely to substitute away from emissions-intensive inputs.

[18]As an example, this model forecasts that electricity prices in Alberta will increase by 21% at a price of \$20/tCO2e.

is a maintained assumption about the prospect for short-run abatement via factor substitution. In the calculation of the effective carbon taxes, production is treated as fixed factor and abatement occurs exclusively through output reduction. While superficially appearing strong, casual evidence suggests that the biases introduced by this assumption may in fact be small. To start, elasticities of substitution between the variable factors of production are small. For example, the mean elasticity of substitution between materials and feed equals 0.05 (calculated based on the production function parameters estimated above). Further, anecdotal evidence, obtained through interviews with farmers, further supports limited substitutability. An example is as follows: during 2016 and 2017, the Province of Ontario experienced very rapid electricity price increases. As a result, cattle producers attempted to be more judicious with their electricity usage. Water heaters, used during the winter months, are viewed as the main source of electricity consumption for cattle operations. In order to offset the higher electricity prices, several, but not all, operators opted to actively manage their equipment, rather than treat the heaters as always-run. They substituted between (potentially uncompensated) labor and energy. An increase in labor hours – active management – took the place of energy-usage – electricity in this context. This response to a sudden increase in input prices illustrates that substitution is possible in the short-run, but it also highlights that its scope is small. More generally, once the baseline supply function is constructed, any counterfactual scenario, representing any degree of abatement, can be implemented.

The effective taxes shown in Table 2 are used in conjunction with the assumption of perfectly elastic demand to inflate farm-specific marginal costs. Following similar steps to those in Cullen and Mansur (2017) for electricity generation, carbon tax-inclusive marginal costs per cwt are given by:

$$MC_{post} = MC_{pre} + t_E \tag{10}$$

where MC_{pre} are the pre-tax marginal costs inferred from the ordered Lagrange multipliers and t_E is the effective tax presented in Table 2.[19] MC_{post} is the post-tax marginal cost per unit output. The main empirical results, presented next, use (10) alongside the equilibrium condition, $p = MC(Q^*)$, to evaluate the MEB of the effective carbon tax scenarios at different output price levels. As a final note, it is important to reemphasize that this analysis is designed to help evaluate cattle farmers' response carbon pricing *in the short-run*. In the long-run, land is likely to bear the majority of any

[19]Figure 1 presented an example where the carbon tax is levied on output. Equation (10) levies the tax on marginal costs. Given the price-taking assumption these are equivalent.

tax.

3 Results

This paper's main qualitative result is that a specific carbon tax yields nonlinear changes in MEB because output prices cause the effective tax rate and elasticity of supply to vary. Figure 2 graphically represents this result for Canadian farmers. Figure 2 contains two panels. The solid blue curve in Figure 2a illustrates the structurally recovered pre-carbon tax, short-run marginal cost curve for cow-calf producers. Situated above this blue supply function is a dashed red curve illustrating a counterfactual scenario with a fixed per unit carbon tax. The counterfactual scenario shown is a \$20/tCO2e levied on all carbon-intensive inputs *and* enteric fermentation from ruminant emissions. As a reminder, \$20/tCO2e is less than the currently legislated carbon price for Canada in 2022 (which is \$50/tCO2e), but the charge on enteric fermentation is not currently part of any province's carbon pricing policy. In Figure 2a, the blue curve "shifts up" to become the dashed red supply function. A recurrent point throughout is that the short-run elasticity of cattle supply increases as a prices fall. This, in turn, explains why the efficiency cost of a carbon tax increases with lower prices. Two references lines, drawn at price levels of \$100 and \$200/cwt of Figure 2, demonstrate this point. The cattle market's output response to the tax is given by the horizontal distance between where these reference lines intersect with the pre- and post-tax supply functions. At an output price of \$100/cwt, the marginal cost curve is flat and there is a large change in the quantity of cattle supplied. This can be contrasted with the reference line drawn at \$200/cwt, where the supply function is steep and the response is smaller.

The changing elasticity of supply feeds into the welfare cost of a fixed carbon tax. Figure 2b, the right-hand panel, illustrates the stringency curves, plotting changes in MEB against output prices. Figure 2b flips the prices from Figure 2a over a 45° line, plotting them along the horizontal axis. The vertical axis of Figure 2b represents MEB in dollars per dollar of carbon tax revenue. MEB is the private marginal efficiency loss (i.e., excluding the environmental benefits) from a \$20/tCO2e carbon tax levied on both inputs and enteric fermentation after adding back tax revenues. Figure 2b demonstrates the nonlinearity of the price-MEB correspondence. Consider a situation where prices are greater than \$200/cwt. With these market conditions, even the most inefficient producers remain in the market. Both the elasticity of supply and the specific carbon tax as a share of output prices are small. As shown along the vertical axis, the private deadweight loss is tiny at only pennies per dollar tax revenue. Compare this high price situation to a lower price of output of \$100/cwt. With output prices at \$100/cwt and a \$20/tCO2e tax on inputs and enteric fermentation, MEB equals a much larger \$0.30 per dollar carbon tax revenue. Key to Figure 2b is that excess burden does not change linearly as prices decrease from \$200 to \$100/cwt. When prices are elevated, small changes in price do not generate noticeable changes in excess burden. If prices are depressed, even small demand shocks lead to meaningful swings in excess burden. For example, a price decline of \$20/cwt from \$100/cwt to \$80/cwt yields a roughly \$0.25 per dollar tax revenue increase in excess burden, a deadweight loss roughly equivalent to a price decline from \$240/cwt to \$100/cwt. The counterfactual shown in Figure 2 is the most stringent in terms of coverage. Nonetheless, it reinforces the paper's main conclusion: *identical carbon taxes* can have different economic costs, and hence competitiveness effects, depending on output prices.

Table 3 and Figure 3 illustrate the empirical results for the alternative counterfactual scenarios. Figure 3 has three panels, one for each coverage level, each with two curves, representing the \$20 and \$40/tCO2e tax levels. These stringency curves show the relationship between MEB and output price for each of the six counterfactual scenarios in Table 2 (including one presented in Figure 2). MEB is calculated according to (2), using the estimated arc elasticity calculated in \$12.50 arc lengths. The curves are then smoothed using lowess. In Figure 3, as in the right-hand panel of Figure 2, MEB is on the vertical axis, but the scales are different for each coverage level. Output prices are along the horizontal axis.

Panel 3a is the most policy relevant counterfactual scenario. It shows the results for the Canadian backstop carbon pricing policy for \$20 and \$40/tCO2e (i.e., for the years 2019 and 2021). The policy conclusion from this figure is that Canada's carbon price floor is unlikely to generate significant (private) deadweight loss for the beef cattle sector. Prices exceeding \$150/cwt in this scenario generate MEBs of less than \$0.01 per dollar tax revenue. Still, the nonlinear relationship between MEB and prices exists. Table 3 provides the exact estimates at three calf prices \$100/cwt, \$150/cwt and \$200/cwt. Table 3 shows that the MEB of, say, the \$40/tCO2e tax is \$0.03 at \$100/cwt but only \$0.01 at \$150/cwt and virtually zero at higher output prices. So, notwithstanding the fact that the stringency of the carbon tax does vary with output prices, Canada's carbon pricing plan is insufficiently stringent, at any price, to meaningful reduce the producer surplus of Canadian cattle farmers. Rent leakage is not a first-order problem given the parameters of the current policy. To be fair, these estimates are for the MEB of a specific carbon tax policy. This is the (marginal) loss of economic efficiency that follows from the policy. The estimates do not reflect the forfeited producer surplus incurred by cattle farmers; the values in Table 3 exclude the market transfer component of leakage. Producers must pay the tax on their inputs, with revenue accruing to the government. Recycling of tax revenues can, in principle, compensate farmers for these market transfers however. In practice, efficient revenue recycling may be challenging in agriculture.

Canada's actual backstop policy can be compared with the second scenario where farm fuels are taxed. Farm fuels are exempted in Canada's national policy and in Alberta and British Columbia. They are priced in Quebec however. Figure 3b and Table 3 shows results from this counterfactual scenario. To start, at output prices above \$150/cwt, there is little difference in the marginal deadweight losses between this scenario and the one where farm fuel is exempted. With a tax of \$20/tCO2e, the cost per dollar tax revenue is \$0.01 even when farm fuels are included in the tax base. Even at \$40/tCO2e, the MEB is still only slightly greater than \$0.01 per dollar tax revenue. Falling prices leads to increasing economic costs and differences are apparent at lower product prices. A \$40/tCO2e tax has a private efficiency cost of roughly \$0.07 per dollar tax revenue when output prices equal \$75/cwt. And even a \$20 tax at \$100/cwt trebles the marginal excess burden from the \$150/cwt level. Still, the cost is a small \$0.03 per dollar and the overall economic efficiency consequences of including dyed fuels destined for use on-farm are minor in the short-run.

Finally, Figure 3c includes emissions from enteric fermentation in the tax base. Adding enteric emissions radically alters the policy implications of carbon taxation for farmers. Net-of-cattle energy costs for a cow-calf operation are typically between 3 to 5%, an energy cost share smaller than many trade-exposed sectors (irrespective of market structure) (Fowlie, Reguant and Ryan, 2016*b*). Once emissions from the digestive processes of cows are included, the adverse competitiveness implications for the cattle industry dramatically change and the nonlinearity of the MEB-price relationship becomes more relevant. As an example, a \$200/cwt output price combined with a \$40/tCO2e carbon that includes farm fuel and emissions from enteric fermentation has a short-run marginal excess burden of \$0.03 per dollar tax revenue. This is the same economic cost as the substantially less stringent backstop carbon pricing policy at combination of a \$20/tCO2e and \$100/cwt output price. Of course, that same \$40/tCO2e tax and \$100/cwt output price with the more stringent policy generates a marginal excess burden of \$0.91. Indeed, once prices fall below this, the industry ceases to exist as the tax causes even the most efficient operations to shutter and the marginal excess burden per dollar tax revenue approaches \$1.00. Key to this scenario is the importance of the tax base. The inclusion of enteric fermentation shows the relevance of a tax's coverage, not just its level, for policy stringency.

Discussion

Source of the Inefficiency and Rent Leakage. It is important to be unambiguous about the source of the distortion in these results. *The stringency of the carbon tax policy varies because the price on emissions does not.* Stated differently, fixing the carbon tax according to emissions-intensity is an implicit policy constraint, one that is a feature of almost all real-world carbon pricing schemes. Carbon taxes are fixed and price-invariant. This constraint moves carbon tax policy from a first- to second-best setting. Demand shocks then produce different levels of tax and emissions levels, but it is not changing output prices that yield the distortion.[20] The distortion emerges because the carbon tax is fixed solely based on emissions-intensity. Two mechanisms then drive the nonlinearity of the MEB curve. First, carbon emissions are taxed on a per unit basis, but tax rates usually matter for deadweight loss calculations – i.e., excess burdens increase with the square of the tax rate. Second, the industry's underlying technology determines the shape of the short-run supply curve. As prices decline, this supply curve become flatter – i.e., excess burdens increase with elasticities. Joining these two principles from the economics of taxation alongside the unilateral implementation of the policy entails the policy's stringency varies with output prices. Extra-jurisdictional shocks thus have the potential to lessen or amplify the (private) economic costs of Canada's climate policy.

Magnitude of MEBs. Carbon taxes are normally believed to introduce fewer distortions than personal or corporate income taxes. This appears to be the case in Canada, except for the extreme counterfactual scenarios that incorporate enteric fermentation. In these cases, even though price levels are realistic, (gross of the social benefits from carbon taxation) MEBs can exceed \$0.90 per dollar tax revenue. In this scenario, estimates rival the efficiency costs of many alternative taxes. For comparison, Browning (1978) found that the last dollar of wage tax, a tax considered to be notably more distortionary than carbon taxes, cost \$0.40. More recently, Dahlby and Ferede (2012, 2018) found marginal costs of public funds for, respectively, the Canadian federal personal and corporate income tax of \$0.17 and \$0.71 per dollar of tax revenue (although the costs of provincial taxes are often much larger).

[20] Changing prices are still Pareto efficient due to the 2nd Fundamental Theorem of Welfare Economics (Phaneuf and Requate, 2016).

Relative Contributions of Rates and Elasticities. Three factors contribute to the increasing efficiency cost of a fixed carbon tax: the tax rate, the elasticity of supply and their product or covariance. Figure 4 examines how MEB changes as these components change. For the counterfactual scenario considered in Figure 2 (a \$20/tCO2e charged on all inputs and enteric fermentation), Figure 4a illustrates the MEB surface. This plot shows how MEB varies as each variable changes. Figure 4b then is a contour plot, showing how different combinations of tax rates and elasticities can be traded-off to keep the market at a fixed level of MEB. While Figure 4 illustrates an interesting decomposition, tax rates and the elasticities are explicitly linked by the state of technology. This means that, conditional on policy parameters, not all points in the figure are feasbile. It is not possible to hold, say, the tax rate constant and vary the elasticity of supply. Figure 4 does however supply useful information for markets with different technologies (or alternative policies).

Linear v. Non-linear Taxes. The nonlinear relationship between MEB and prices is a direct consequence of the linearity of the per tCO2e carbon charge. This nonlinear relationship can be avoided by replacing the linear tax with a nonlinear scheme. This observation would seem to highlight an unmissable policy recommendation: implement nonlinear taxes. Yet, nonlinear taxes are administratively cumbersome, costly and often impractical (Phaneuf and Requate, 2016). Moreover, nonlinear taxes are more opaque, thus giving special interests greater capacity to lobby for weak stringency. Canada's backstop policy has adopted a linear tax, eschewing nonlinear options. It seems implausible that a similar broad-based nonlinear carbon tax could be developed for a country such as Canada.[21]

Optimal Carbon Taxation. In first-best settings, optimal carbon taxes are equal to the marginal damage of an additional unit of CO2e, with marginal damage measured as the social cost of carbon. Carbon taxes however typically represent one of several revenue sources in an economy with other distortions. In a second-best setting, Sandmo (1975) demonstrated the so-called additivity property of externality correcting taxes: an externality correcting Pigouvian tax only affects the formula for that commodity's rate. Moreover, in the second-best, the measurement of environmental damage changes. Carbon dioxide emissions are valued in terms of tax revenue, so the additive externality term is the ratio of marginal damage to the marginal cost of funds (e.g., as in (1)). This paper demonstrated that for unilaterally implemented carbon taxes the marginal

[21] This being said, the province of Alberta has adopted price-sensitive royalty rates for conventional and bitumen resources (Crisan and Mintz, 2016; Plourde, 2009). But this serves as an example of the challenges of nonlinear taxes. First, it is unknown whether the slope of the royalty schedule matches the marginal cost of extraction. Second, an administratively costly, formal panel was created to devise this scheme.

cost of funds depends on extra-jurisdictional conditions. That is, even when marginal damage is constant (set at say the global social cost of carbon), the marginal cost of funds may vary across a wide range – in this situation, even with constant marginal damage the optimal tax may swing by up to 40%, posing challenges for the tax-setting authorities (and, hence, real-world taxes are unlikely to be optimal).[22]

Emissions Leakage. This study concentrated on the market transfer and rent leakage dimensions of leakage. An equally important component of unilateral environmental regulation is emissions leakage. Emissions leakage depends on both the magnitude of foreigners' output response to Canadian policy and the carbon-intensity of their production. Like in many studies on trade and the environment (e.g., Copeland and Taylor, 2004; Tombe and Winter, 2015), emissions were assumed to be proportional to inputs. Indeed, a core assumption of the counterfactual exercises is that farms are heterogeneous with respect to marginal costs (determined by productivity) but homogeneous with respect to emissions intensity. Given the Canadian cattle industry, this assumption is viewed as reasonable, but this may not be true internationally. Global feeding practices vary substantially and it may be that foreign production is more or less emissions-intensive than foregone domestic production. The change in global emissions therefore depends on differences between domestic and foreign production technologies. Fowlie and Reguant (2018) present empirically implementable formula for estimating the extent of emissions leakage.

4 Conclusion

Pigouvian taxation is the most frequently advocated instrument to correct environmental externalities. Pigouvian taxes are simple, straightforward to administer and cost-effective tools to improve social welfare. Still, remarkably few jurisdictions have embraced policies such as carbon taxes. Indeed, as is the case with carbon taxes and Canadian farmers, Pigouvian taxation is often met with open hostility. Opponents claim that the policies are poorly designed or that they disproportionately disadvantage important constituents. This paper attempts to unpack the economic channels explaining these sentiments.

[22]Notwithstanding this point, of course, uncertainty in the marginal damage swamps variation in the marginal cost of funds and many industries are unlikely to experience the same price volatility as commodity markets. As such, reasonable approximations to optimal carbon taxes should be within reach.

Two basic propositions from the economics of taxation are shown to potentially explain industry opposition to carbon taxes. The excess burden of a tax increases both with the square of the tax rate and with the size of elasticities. Based on these principles, industries may be susceptible to nonlinearly increasing policy stringency when specific carbon taxes are unilaterally implemented. This changing stringency of carbon taxes appears to be underappreciated in much of climate policy, likely because empirical methods to adequately measure these channels were unavailable. The contribution of this paper is to provide one approach to recover marginal cost schedules and to apply the method to a sample of Canadian cattle producers.[23]

To the best of my knowledge, previous research into carbon taxation has failed to consider the how tax rates, elasticities and demand shocks induce nonlinear changes in industry competitiveness. In fact, more generally, empirical research into the economic costs of taxes appears to have relegated this point to a footnote. This paper is a start. The method presented here offers substantial room to relax key assumptions and study other sectors. Ultimately, the variable stringency of carbon taxation is something for which small open economies such as Canada must be cognizant as it may explain some part of key industries' opposition to carbon taxation.

[23]Beyond the empirical methodology, the nonlinear relationship between product prices and stringency of carbon taxation has implications for basic policy design and revenue recycling mechanisms. First-best policy must acknowledge the heterogeneity in firm costs, which requires accurate knowledge of the supply function and access to appropriate revenue recycling mechanisms (e.g., lump-sum transfers). Addressing this heterogeneity is likely infeasible in many settings, so second-best designs, based on Diamond's (1973) weighted-average method for externality correction, are likely needed (e.g., Knittel and Sandler, 2013). Moreover, the changing elasticity of the supply underscores a first-order challenge in recycling revenues to farmers. Revenue recycling is an equity issue. Revenue recycling attempts to maintain the marginal incentive to reduce emissions while reducing the average cost the regulation. Difficulties arises when large output effects induce frequent firm entry and exit as is the case when the primary channel of abatement is output contraction. Identifying firms that exit due to the carbon tax versus those that would exit in the absence of a tax is challenging. Revenues should only be recycled to the former class and not to fundamentally inefficient producers. Practically, separating these groups with an efficient and political palatable mechanism could be difficult. Likewise, subsidies and hybrid schemes which are designed to mitigate competitiveness effects can exacerbate existing distortions, are subject to lobbying pressure and must be "calibrated" to particular industry conditions (Tombe and Winter, 2015). Exemptions such as those granted on fuel used on-farm are usually as viewed as inefficient methods to reduce competitiveness concerns. However, given the agricultural industry's opposition, they may be the political price of unilateral carbon pricing.

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5 Figures

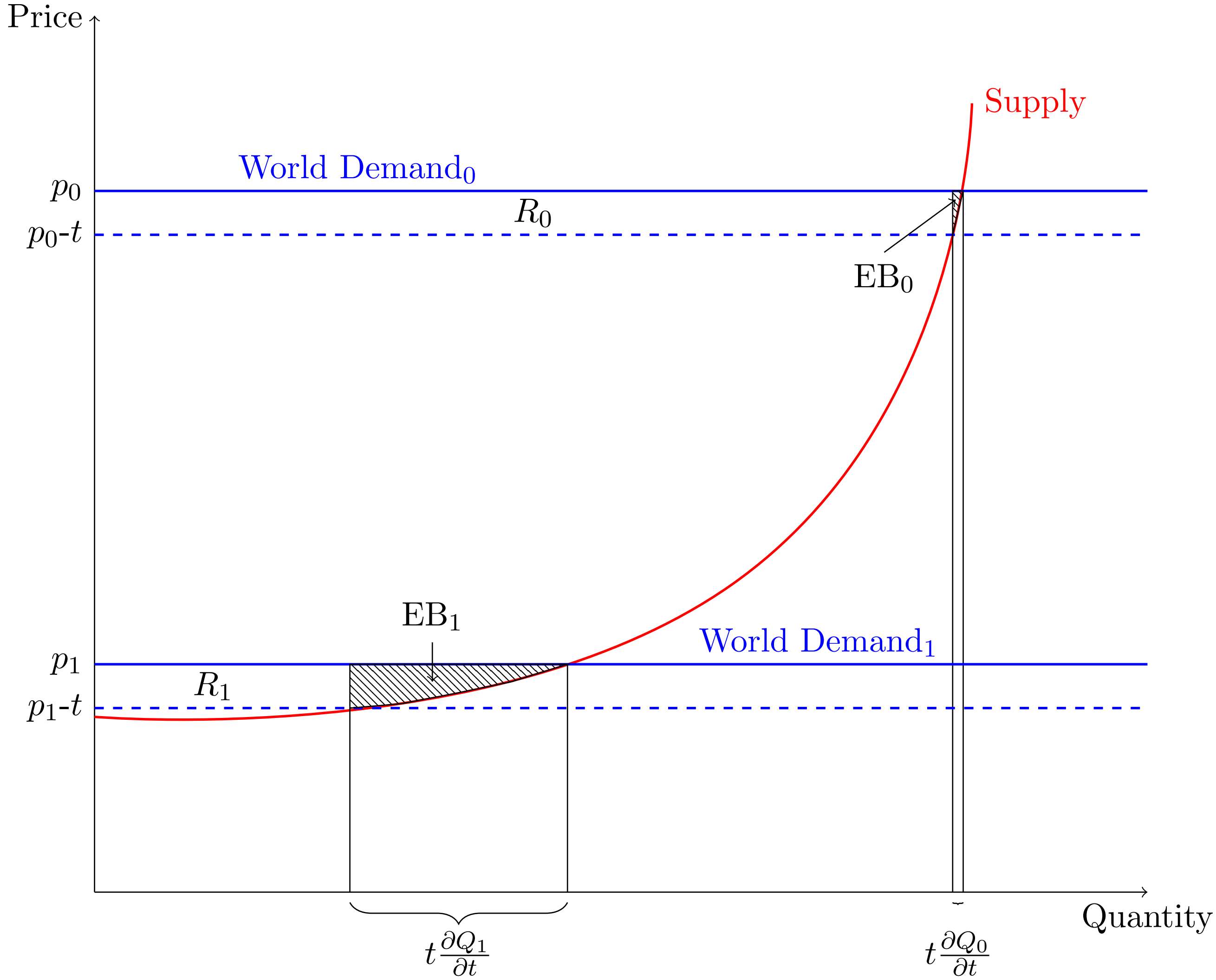
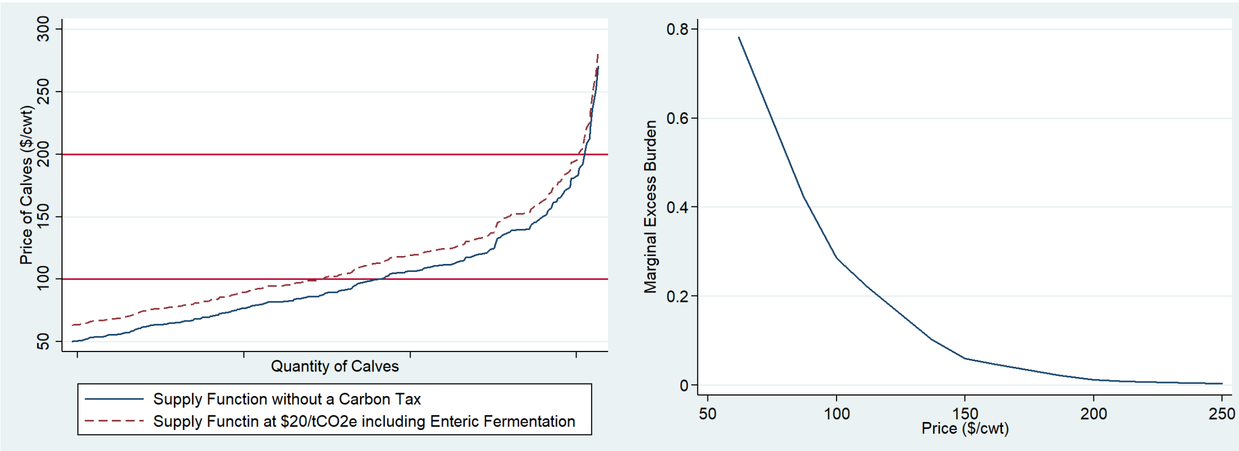
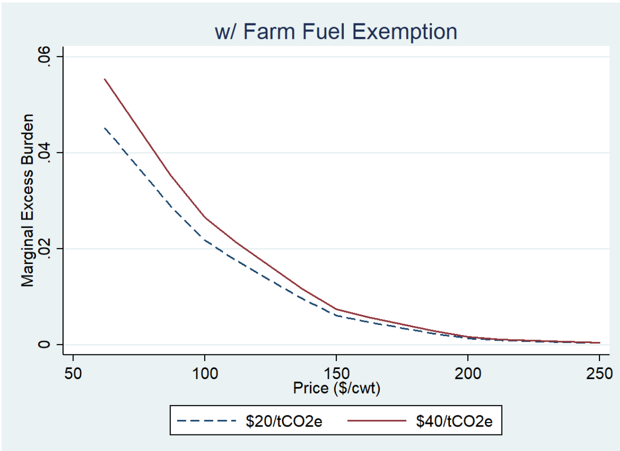


Figure 1: Excess Burden of a Fixed Carbon Tax at Different Product Prices

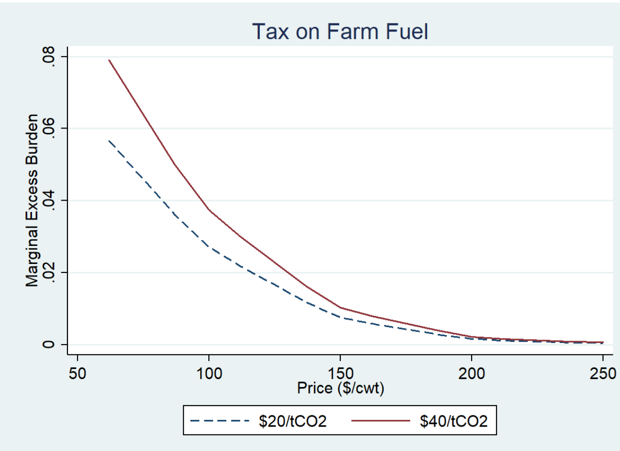


(a) Supply Function (b) Marginal Excess Burden

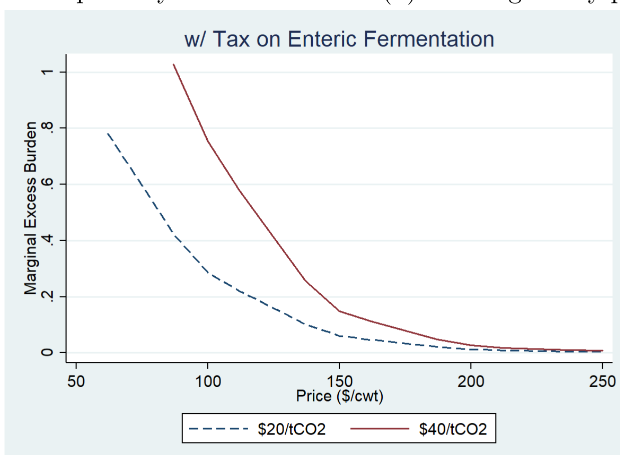
Figure 2: Relationship between Marginal Costs and Marginal Excess Burden for an Effective $20/tCO2e Carbon Tax incl. Farm Fuel and Enteric Fermentation



(a) Existing Backstop Policy

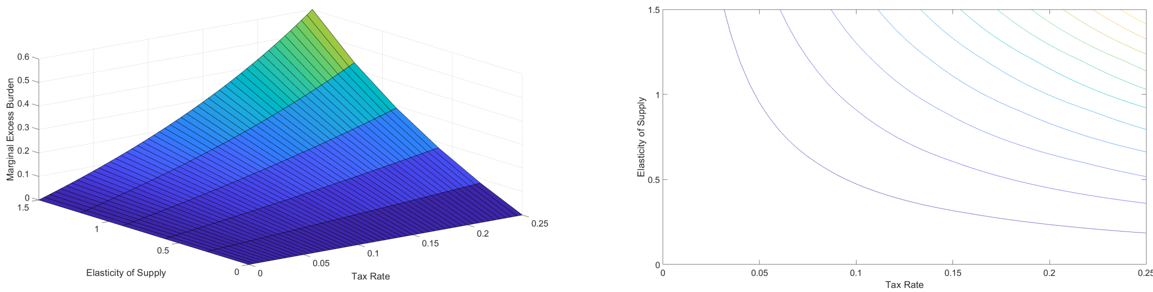


(b) Existing Policy plus Tax on Farm Fuel



(c) Existing Policy plus Tax on Farm Fuel and Enteric Fermentation

Figure 3: Marginal Excess Burden of Carbon Taxes



(a) Marginal Excess Burden Surface

(b) MEB Level Sets in Tax Rate-Elasticity Space

Figure 4: Sensitivity of Marginal Excess Burden to Changes in Elasticities and Tax Rates

6 Tables

Table 1: Estimates of the Output Elasticity for Materials and Energy

	OLS	OLS-FE	CF
Output elasticity	0.173***	0.092**	0.159**
	(0.034)	(0.032)	(0.035)
N	400	400	400
Returns to scale	0.95	0.54	0.92

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Standard errors for OLS and OLS-FE clustered on individual farms. Standard errors are bootstrapped for CF.

This table illustrates the output elasticity of calf production with respect to material and energy inputs for three estimation methodologies: least squares, fixed effects and control function models.

Table 2: Effective Carbon Tax for Six Counterfactual Policy Scenarios

	\$20/tCO_2e	\$40/tCO_2e
Existing policy	1.55	1.87
+ Tax on farm fuel	1.91	2.58
+ Tax on farm fuel and enteric fermentation	12.80	24.35

This table illustrates the six carbon pricing scenarios considered in this analysis. Two tax rates – \$20 and \$40/t$CO_2$2 – and three tax bases are included. Appendix C describes the methodology used to construct these scenarios.

Table 3: Marginal Excess Burden on Carbon Taxes, Deadweight loss per Dollar Tax Revenue

Output price	\$100/cwt	\$150/cwt	\$200/cwt
		\$20/tCO_2e	
Existing policy	0.024	0.008	0.002
+ Tax on farm fuel	0.030	0.010	0.002
+ Tax on farm fuel and enteric fermentation	0.276	0.075	0.014
		\$40/tCO_2e	
Existing policy	0.029	0.010	0.002
+ Tax on farm fuel	0.041	0.013	0.003
+ Tax on farm fuel and enteric fermentation	0.903	0.169	0.029

This table displays the marginal excess burden, or welfare cost per dollar of tax revenue, for each of three output prices – \$100, \$150 and \$200/cwt – the scenarios presented in Table 2.

APPENDIX – FOR ONLINE PUBLICATION

A Brief Overview of Carbon Pricing in Canada

In October 2016, the Government of Canada announced that all Canadian provinces and territories would be required to price CO_2e emissions starting January 1, 2018. Political and administrative challenges subsequently delayed the launch to January 1, 2019. The enacting carbon pricing legislation established a "backstop" policy, whereby the federal government would impose carbon taxes on non-compliant provinces – those provinces that are unable or politically unwilling to develop province-specific climate policy.[24] Jurisdictions are encouraged to tailor province-specific programs for their particular economic conditions, but the backstop legislation mandates minimum stringency and coverage. Prices start at $20/tCO2e in 2019, increasing by $10 per year until 2022 when the tax or target cap-and-trade permit price equals $50/tCO2e.

Textbook carbon levies apply to all greenhouse gas emissions with the effective rates based on equivalent carbon content. Canada's backstop policy, however, focuses on combustion emissions, exempting process emissions. This shrinks the tax base to approximately 70% of total national emissions. Excluded from the tax base are fugitive emissions from landfills and soils and manufacturing process emissions such as those in cement production (Fowlie, Reguant and Ryan, 2016*b*). Also excluded is fuel used on-farms as well as the largest remaining unpriced source of emissions: methane emissions from enteric fermentation, the digestive processes of cows and other ruminants. Several public calls have stated that the tax should cover enteric fermentation (e.g., Dion, 2016), but to date neither the federal government nor the provinces have signaled willingness to impose a tax on biological emissions.[25]

When the federal government introduced its backstop legislation, four provinces had already committed to pricing CO2e. Alberta introduced a carbon tax and Ontario launched a cap-and-trade system on January 1, 2017. British Columbia introduced its carbon tax in 2008. The province of Quebec had a small carbon tax on fuel beginning in 2007, but initiated its more comprehensive cap-and-trade market, a market that is linked with California, in 2013. When it was introduced, British Columbia's carbon tax combined a unique set of policy characteristics that earned it plaudits from economists (Murray and Rivers, 2015). Subsequent tweaks reduced the British Columbian tax's overall efficiency. Notably, in 2012, the province exempted all dyed fuels intended for on-farm use, an exemption that arose from the agricultural sector's competitiveness concerns. The exemption's objective was to help domestic agricultural producers compete more effectively with farmers in the US and Mexico. British Columbia is not unique in exempting agriculture from its carbon tax as neither the Alberta nor federal backstop carbon taxes apply to farm fuels. In contrast, Ontario and Quebec's cap-and-trade systems (programs linked with California) do apply to farmers.

[24] Notably, in an attempt to avoid pricing emissions, Saskatchewan, the Canadian province with the largest agricultural output is currently challenging the federal government's authority to impose a carbon tax.

[25] Internationally, no jurisdiction regulates emissions from the biological processes of livestock (De Cara, Henry and Jayet, 2018).

B Additional Background on Canadian Cattle Industry

Distribution of Cattle Prices over Time

A theme of this study is that commodity price fluctuations – demand shocks – change the stringency of a per unit carbon tax. The extent to which stringency varies depends on the empirical range of cattle prices. Figure 5 shows the distribution of Albertan feeder calf prices over two time scales. First, the transparent histogram shows prices from January 2011 through July 2017. Prices range from a low of \$110/cwt to a maximum of \$258/cwt, with a mean of \$164.62/cwt. This recent experience can be compared to the solid gray histogram. This graph extends the time frame an additional twenty years, starting in January 1990 and ending in July 2017. A starkly distinct pattern is observable. Notably more mass is located at lower prices combined with greater spread. For this extended period, the minimum price equaled \$64/cwt with a mean that is more than 30% lower at \$113.31/cwt. Bovine spongiform encephalopathy (BSE), or mad cow disease, explains the price divergence over the two periods. Canada experienced a BSE crisis from May 2003 through to the end of 2004. Exports of Canadian cattle were severely restricted during this period, hence domestic prices deviated from global prices. This was a major demand shock for the industry and private interviews with producers suggests that the memory of the crisis (and the ensuing price variability) remains. For this paper's purposes, Figure 5 demonstrates that cattle prices do span a wide-range. Hence, it is possible that elasticities of supply and tax rates do meaningfully change over realized prices.

Price-taking and Unilateral Carbon Taxation

Verifying that cattle prices vary through a wide range satisfies one pre-condition for the subsequent analysis. A second requirement involves the price-taking assumption. More than 50% of Canadian production is exported, yet Canadian exports comprise only 1.9% of the global market (USDA, 2017).[26] This suggests that it is likely that Canadian producers lack market power and are unable to influence prices. Based on this, it is conventional to invoke the small open economy assumption and merely assert that Canadian producers are unable to pass-through unilaterally imposed carbon costs. The argument is as follows: if the Government of Canada imposes its carbon tax on cattle farmers,[27] operations bear the entire cost of these levies because international competition ensures that domestic producers have no capacity to influence global commodity prices. This argument is illustrated in Figure 6. The familiar competitive, partial equilibrium analysis of a carbon tax is depicted in Figure 6a, with initial equilibrium price and quantity are p^* and q^*. A carbon tax, levied on producers in this case, vertically shifts the supply function. Producers receive $(p^* - p_p)$ less per cow, while consumers pay $(p_c - p^*)$ more. This last point is essential: post-tax consumer prices increase in this scenario. The demand response ensures that the tax burden is split between between consumers and producers with the incidence determined by the relative elasticities of

[26]The United States, Europe, Brazil, Argentina and Australia each produce substantially more pounds of live cattle than Canada.

[27]Or indirectly prices emissions as is done in Ontario and Quebec.

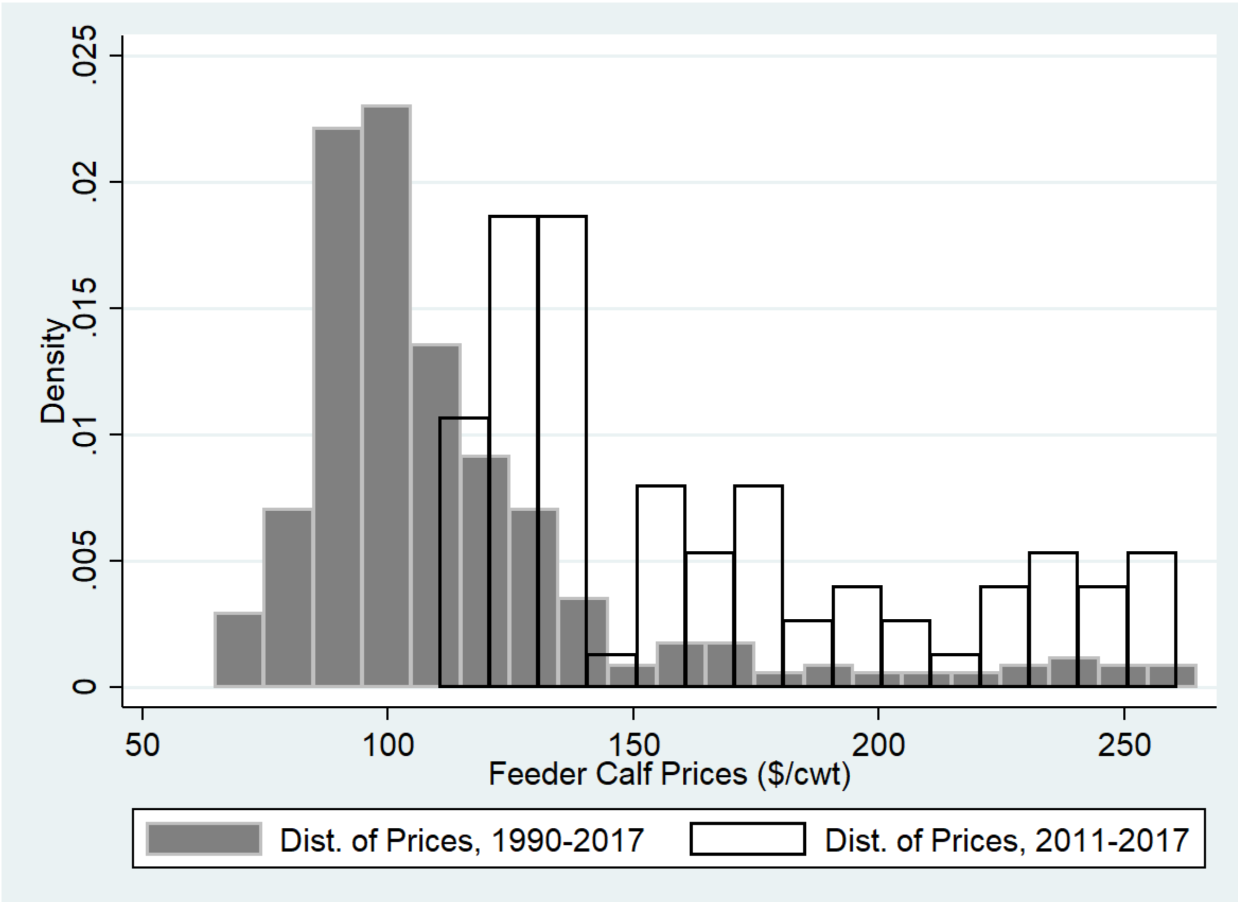
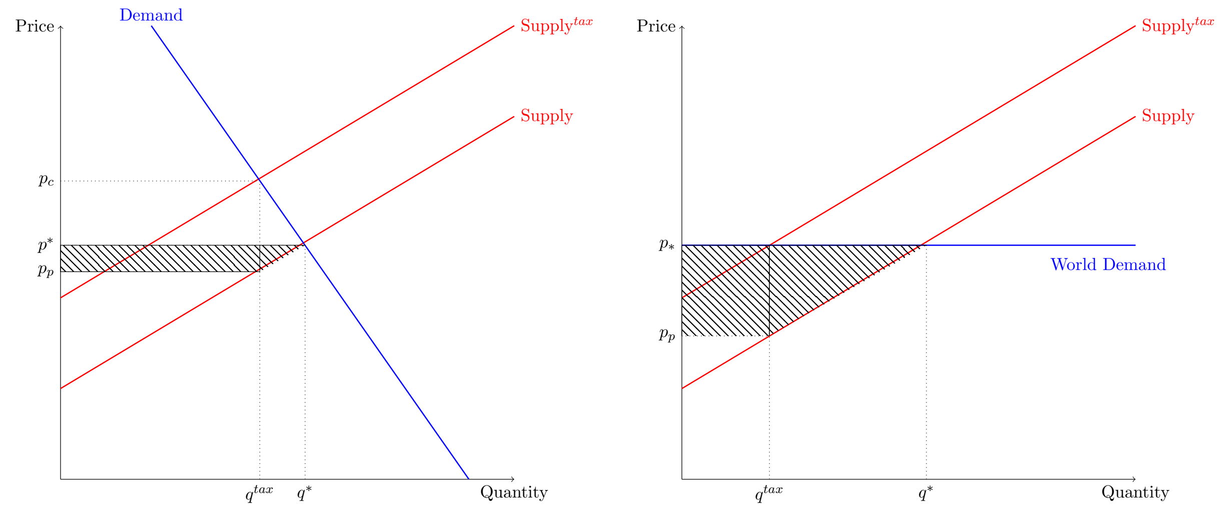


Figure 5: Distribution of Feeder Calf Prices

demand and supply. This conventional analysis can be compared with the small open economy assumption shown in Figure 6b. In Figure 6b, producers face the same carbon tax as in Panel 6a, but equilibrium prices do not change. The demand channel disappears as producers in a small open economy comprise too small share of the global market. Domestic producers thus receive $(p^* - p_p)$ less per unit output, an amount equal to the full value of the tax. Rent leakage equals $(q^* - q^{tax})$, because foreign production displaces domestic production.

While the argument represented in Figure 6 is familiar, supporting empirical evidence for it is scant. This is because country- or region-specific shocks are required to statistically identify pass-through – i.e., to test whether equilibrium prices respond to local changes in marginal costs – and these sources of variation are rare. Shocks, such as increases in fertilizer or oil prices, are usually global in nature, so affect the entire cattle industry. This includes producers in Canada, but also operations elsewhere in the world. The important characteristic of Canada's carbon pricing policy, however, is that it is unilateral. This means that it will only change the cost structure of Canadian enterprises while leaving producers in the rest of the world unaffected.

It is possible to investigate the small open economy assumption by examining province-specific



(a) Effect of a Carbon Tax with a Demand Response (b) Effect of a Unilaterally Implemented Carbon Tax

Figure 6: Effect of Carbon Taxes on the Cattle Sector

changes in diesel taxation. Following Marion and Muehlegger (2011), feeder calve prices are regressed on province-specific changes in diesel taxes after controlling for time and geographical factors. If local shocks to input prices lead to higher output prices, pass-through rates will be positive, suggesting that Canadian producers have some market power and the small open economy assumption is questionable. Conversely, if producers are not able to pass-through idiosyncratic tax increases, it suggest that farmers are indeed price-takers. The basic regression for this analysis is:

$$\text{Feeder Price}_{it} = \alpha \text{Diesel Tax}_{it} + \tau_t + \gamma_i + \epsilon_{it} \tag{11}$$

where Feeder Price$_{it}$ refers to the province-specific feeder calf auction price for the provinces of Alberta and Ontario. The analysis is restricted to Alberta and Ontario as these are the only provinces for which calf price data are available. Diesel Tax$_{it}$ is the province-specific component of the diesel fuel excise tax.[28] Like with carbon pricing, fuel taxes have both direct and indirect effects on agricultural operations. Diesel is a direct input into production, but it is also a factor in other input markets. Key to the analysis here is that the tax changes are unique to each jurisdiction – i.e., they only change prices in one province at a time – so have idiosyncratic region-specific statistical variation that enables identification of tax pass-through rates for the highly-traded beef industry if it exists. Both prices and diesel taxes are logged, so α, the parameter of interest, should be interpreted as the pass-through elasticity. Also included in (11) are time fixed effects, τ_t, and province fixed effects, γ_i.

Table 4 shows that provincial excise taxes on fuels have little economically or statistically meaningful effect on cattle prices. Two columns of results are presented. Column (1) is the base specification and shows a pass-through elasticity equal to 0.02. While positive, the standard error includes zero and is reasonably precise. This suggests little ability to pass-through unilateral imposed taxes to final prices. Column (2) adds a province-specific time trend and finds essential

[28] Canada's federal government also levies taxes on fuel, but these are common to all provinces.

Table 4: Effect of Diesel Taxes on Calf Prices

	log(Feeder cattle prices)	
log(Provincial diesel tax)	0.019	0.019
	(0.066)	(0.066)
N	480	480
Year FE	Y	N
Month FE	Y	Y
Province FE	Y	Y
Province-specific trends	N	Y

Robust standard errors in parentheses

This Table examines the small open economy assumption underlying the counterfactual analysis. Two regressions are presented, with (log) feeder cattle prices regressed on (log) diesel taxes. Coefficients and standard errors illustrate the little statistical support that the pass-through elasticity is different from zero or economically meaningful, thus supporting the assumption that farmers are price-takers.

identical results, showing a point estimate of 0.02 with a standard error of 0.07. Given the difficulty in finding region-specific price variation, these regressions emphasize that it is reasonable to assume that Canadian producers are price-takers.

C Constructing the Counterfactual Scenarios from Enterprise Budgets

Carbon taxes have direct and indirect implications for cattle operations' marginal costs. Energy, electricity and farm fuel, are, of course, directly taxed. This is where the majority of an enterprise's direct increases in costs arise. Increases in indirect costs come mainly through higher prices of feed as feed which comprises the largest share of total costs. The description in this Appendix mirrors Schaufele (2018).

A cow-calf farm's carbon tax-induced marginal cost increase from Canada's backstop carbon pricing policy is estimated by combining several models. These models are solely to estimate the effective carbon tax for cow-calf farms. There are two enterprise budgets or cash flow models. The primary enterprise budget is for a "typical" Albertan cow-calf farm. This is provided by the Alberta Ministry of Agriculture and Forestry (AAF, 2015), but are checked for reasonableness against similar models created by Ontario's Ministry for Agriculture, Food and Rural Affairs and Canfax (the research arm of the Canadian Cattlemen's Association). Table 5 shows this budget. Column (1) represents the mean estimated costs per weaned calf. These costs are based on the five year average accounting data. Accounting data are clearly imperfect: average costs typically are viewed as a poor proxy for marginal costs. Yet, as this model is only used to estimate the effective tax, the error is viewed as acceptable.

As is evident in Table 5, feed, which is comprised of winter feed, pasture rental and supplement (mineral), represents roughly 70% of an operation's variable costs. The remaining six columns of Table 5 reflect the distinct carbon pricing scenarios. Two carbon prices – \$20 and \$40/tCO_2e – are examined, as are three levels of coverage: with a farm fuel exemption (as in Alberta, British Columbia and the federal backstop), without a farm fuel exemption (as in Ontario and Quebec) and a tax on farm fuel plus enteric fermentation.

While not shown, increases in winter feed costs are estimated by combining similar "crop" enterprise budget models provided by the Alberta Ministry of Agriculture and Forestry (AAF, 2015). For the purposes of this study, the most important inputs into the winter feed enterprise budgets are fuel and fertilizer. Fertilizer is a factor of production that has a high CO2e intensity.[29] The results from Rivers (2017) are used to determine the increase in fertilizer costs. Rivers (2017) developed a computable general equilibrium model of the Canadian economy to calculate the carbon policy induced price changes of specific agricultural inputs. At \$20/tCO2e, Rivers (2017) forecasts that fertilizer prices will increase by approximately 3.5%, while chemical prices are expected to increase by 0.1%. These are linearly extrapolated for the \$40/tCO2e scenario. These cost increases for fertilizer and chemicals were incorporated into the enterprise budgets to calculate the expected per tonne-feed increase in costs. Fuel is the other major input in these crop budgets, so the exemption or non-exemption of on-farm fuel use has a central role in determining indirect cost increases through inputs: that is, if farm fuel is exempt, the increase in the cost of feed is smaller than if it is not exempt. This increase in feed costs is an indirect effect of the carbon tax for feedlots. While the results in this paper use enterprise budgets from the Alberta Ministry of Agriculture and Forestry, again estimates using models from the Ontario Ministry of Agriculture, Food and Rural Affairs were also used to calibrate the Alberta values.

Next, the increase in electricity prices due to carbon pricing may be large, especially in Alberta the location of this study. A substantial share of Albertan electricity is from coal-fired generation, so carbon taxes will affect utility costs. (Other jurisdictions in Canada do not face similar pressures as they have substantial hydroelectric or nuclear power.) Cattle farms usually do not use much electricity. Still, determining how much the price of electricity will increase is challenging. Several factors such as the fuel mix of existing generation (natural gas or coal) and the potential for market power on the part of generators complicate matters. These factors interact with the output-based rebate system in the backstop carbon pricing policy. Alberta has clearly articulated how its output-based allocations apply to its electricity sector (and it appears highly probable that the federal government will adopt a system that is identical to Alberta's). Brown, Eckert and Eckert (2017) developed a detailed model of Alberta's electricity sector that incorporates each of these elements: output-based allocations, market power and fuel mix. They forecast that a \$20/tCO2e will cause a 21% increase in Alberta electricity prices. This estimate is used in the \$20/tCO_2e scenarios. An increase of 31% is used for the \$40/tCO_2e scenario to reflect the rapidly changing mix of generation.

[29] Nitrogen and ammonia, for example, comprises roughly 90% of the cost of feedstock in the US. The production of ammonia consumes roughly 3% of global natural gas. Ammonia is produced via the Haber-Bosch process, a fixed factor nitrogen-fixation reaction that requires 32.5 MBTU per 1 tonne ammonia (see, e.g., Boulamanti and Moya, 2017)

The final step involves calculating the emissions attributable to enteric fermentation. Each cwt of live weight is assumed to produce 0.54431tCO2e/cwt. This value was calculated by converting live weight from lbs to kg and then deflating 0.6 to obtain a carcass weight in kg. Then a fixed conversion factor obtained from the FAO (2017) was applied to this carcass weight. Based on the FAO (2017), enteric emissions are assumed to be emitted at a rate of 20 kgCO2e/kg carcass weight. It is slightly smaller than the 21.73kgCO2e/kg carcass weight applied in Beauchemin et al. (2010), but slightly larger than the 17.2kgCO2e/kg carcass weight rate determined in Vergé et al. (2008) and the 12.0kg CO2e/kg carcass weight in Legesse et al. (2016). Emissions per weaned steer were then obtained per cwt and incorporated into the cash flow model.

Table 5 presents the results for the six cost scenarios considered. All calculations are based on weaned steers that are sold at 650lbs.

Table 5: Estimates of Effective Carbon Tax for Cow-calf Operations

		Carbon Pricing Scenarios					
		Farm Fuel Exemption		*Tax on Farm Fuel*		*Enteric Fermentation*	
	Baseline	\$20/tCO_2e	\$40/tCO_2e	\$20/tCO_2e	\$40/tCO_2e	\$20/tCO_2e	\$40/tCO_2e
Feed	476.62	482.45	482.98	483.96	486.12	483.96	486.12
Labor	47.29	47.29	47.29	47.29	47.29	47.29	47.29
Utilities and fuel	30.54	34.26	35.31	35.12	36.87	35.12	36.87
Other costs and overhead	133.76	134.26	134.76	134.26	134.76	134.26	134.76
Total variable cost	688.22	698.26	700.34	700.63	705.04	700.63	705.04
Cost of digestive emissions per cwt	-	-	-	-	-	10.89	21.77
Cost per cwt	105.88	107.43	107.75	107.79	108.46	118.68	130.23

The cash flow model is based on AAF (2015) for a weaned calf sold at 650lbs. Values in the table represent the average 5-year costs of Canadian cow-calf farms, adjusted for the scenario described. "Other costs and overhead" include veterinary and medicine, interest, marketing and overhead costs.